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Dumitriu et al.

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(54) **SYSTEM AND METHOD FOR ROUTING SERVICE REQUESTS**

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(73) Assignee: **AMAZON TECHNOLOGIES, INC.**, Seattle, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 219 days.

This patent is subject to a terminal disclaimer.

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(22) Filed: **Jun. 22, 2017**

(65) **Prior Publication Data**

US 2018/0013693 A1 Jan. 11, 2018

Related U.S. Application Data

(63) Continuation of application No. 14/454,629, filed on Aug. 7, 2014, now Pat. No. 9,692,708, which is a (Continued)

(51) **Int. Cl.**

G06F 15/173 (2006.01)
H04L 12/911 (2013.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H04L 47/70*** (2013.01); ***H04L 1/0018*** (2013.01); ***H04L 29/08144*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC . H04L 47/70; H04L 29/08144; H04L 1/0018; H04L 67/2814; H04L 67/1029;

(Continued)

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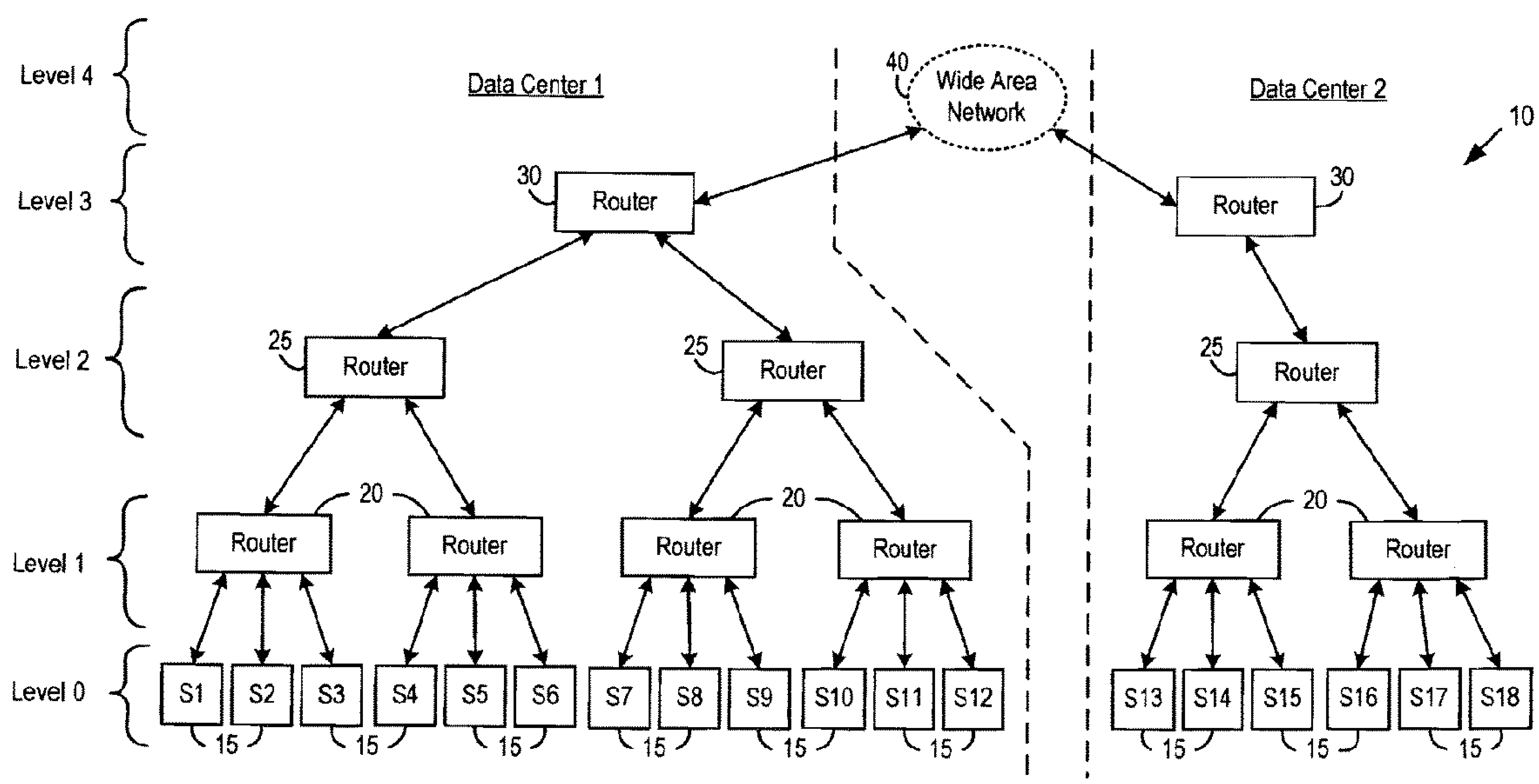
(57) **ABSTRACT**

A computer-implemented method routes service requests to services in a service framework provided by a plurality of hosts. The method comprises receiving a service request for a service in the service framework and discovering a plurality of candidate hosts that host the service. The plurality of candidate hosts are a subset of the plurality of hosts. The method further comprises selecting a candidate host from the plurality of candidate hosts based on measured latencies for the plurality of candidate hosts and routing the service request to the selected candidate host.

14 Claims, 16 Drawing Sheets



Related U.S. Application Data

continuation of application No. 13/770,818, filed on Feb. 19, 2013, now Pat. No. 8,805,991, which is a continuation of application No. 13/269,479, filed on Oct. 7, 2011, now Pat. No. 8,396,957, which is a continuation of application No. 12/399,881, filed on Mar. 6, 2009, now Pat. No. 8,037,186, which is a continuation of application No. 11/375,652, filed on Mar. 14, 2006, now Pat. No. 7,519,734.

(51) **Int. Cl.**
H04L 29/08 (2006.01)
H04L 1/00 (2006.01)
H04L 29/14 (2006.01)

(52) **U.S. Cl.**
CPC ***H04L 67/1002*** (2013.01); ***H04L 67/1029*** (2013.01); ***H04L 67/2814*** (2013.01); ***H04L 67/327*** (2013.01); *H04L 67/101* (2013.01); *H04L 67/1019* (2013.01); *H04L 69/40* (2013.01)

(58) **Field of Classification Search**
CPC ... H04L 67/327; H04L 67/1019; H04L 69/40; H04L 67/1002; H04L 67/101
See application file for complete search history.

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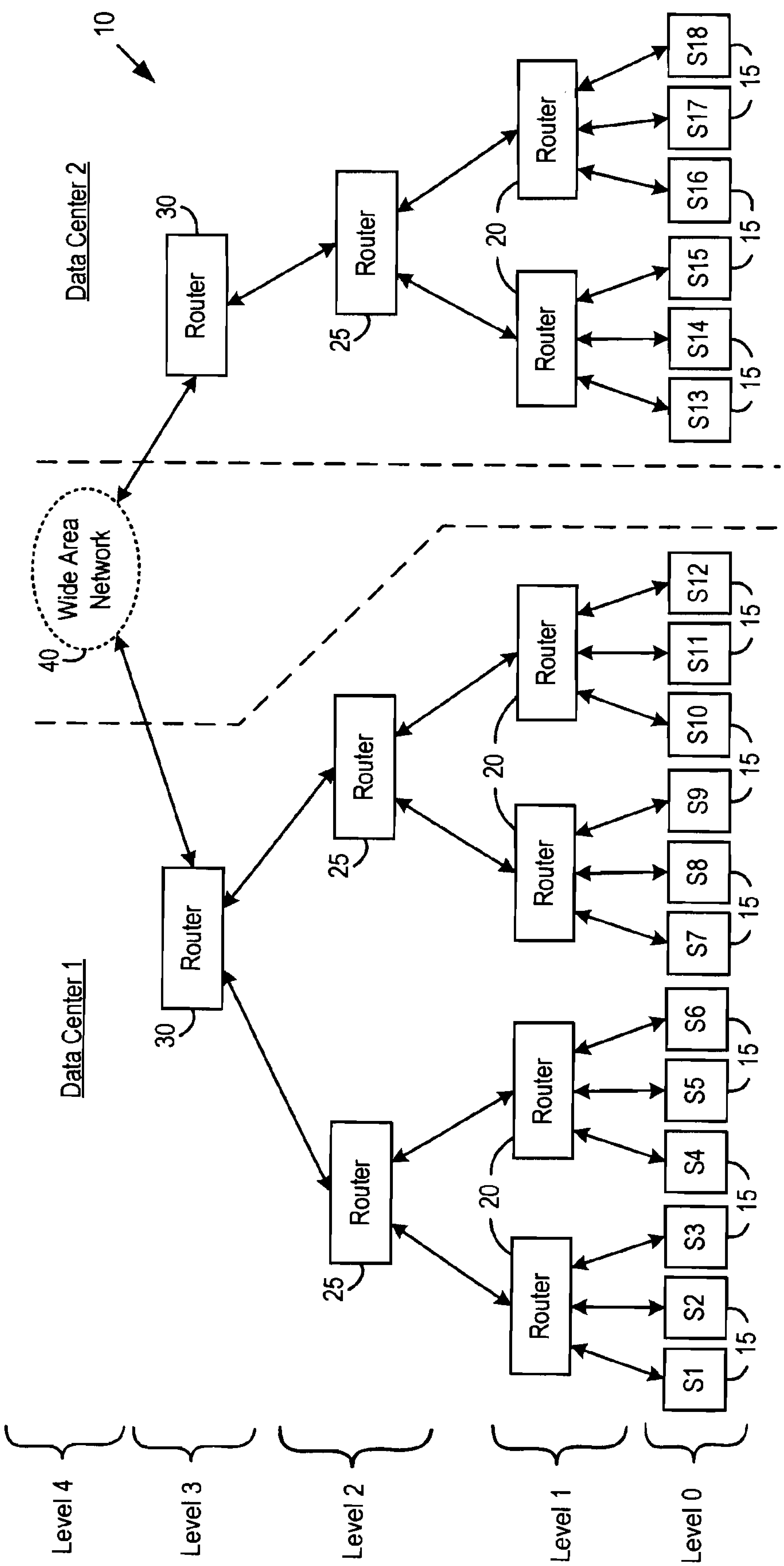

10
Data Center 1
Data Center 2
Wide Area Network
40
Router
30
25
20
15
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
Level 4
Level 3
Level 2
Level 1
Level 0

FIG. 1

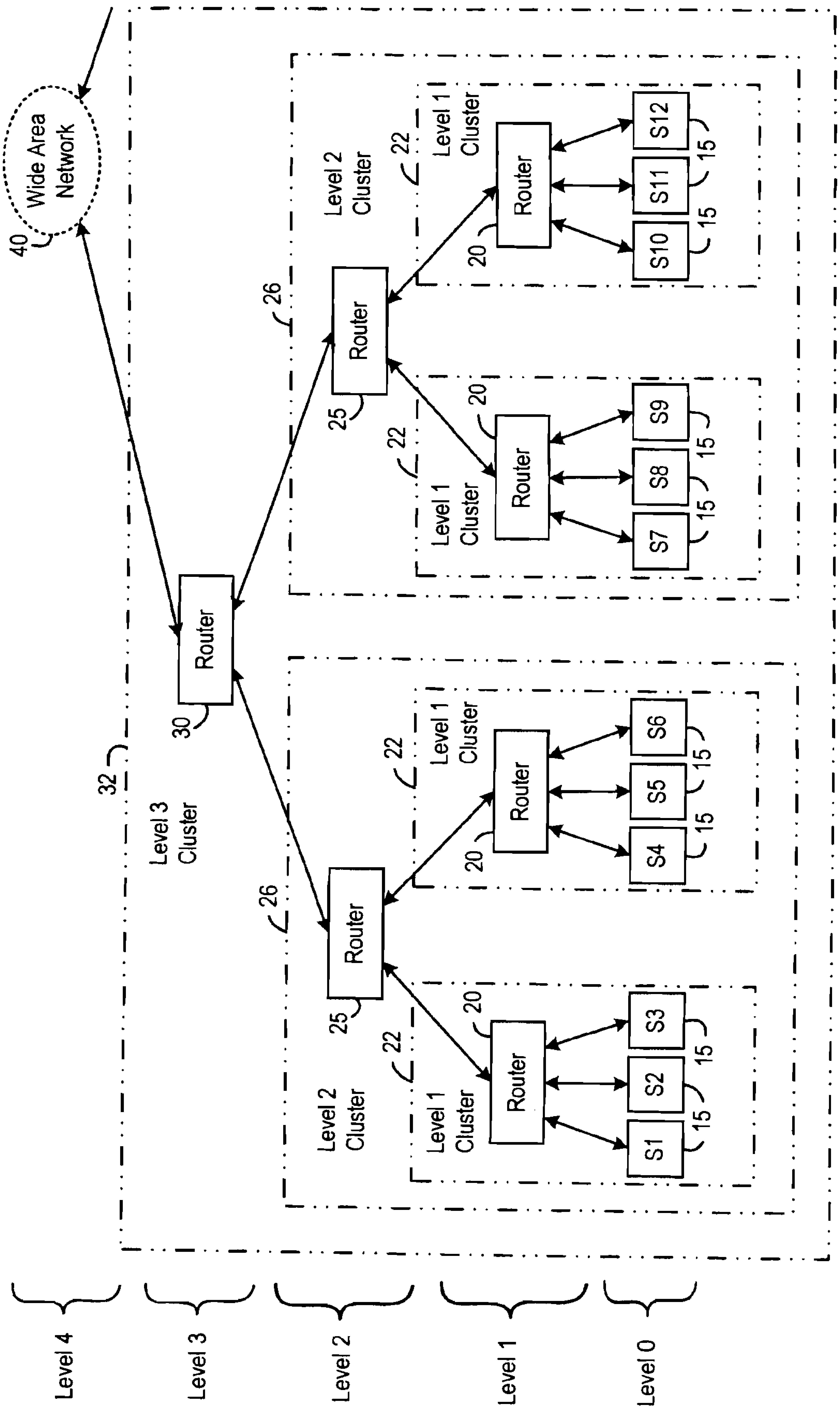

Wide Area Network
40
Level 3 Cluster
32
Router
30
Level 2 Cluster
26
Router
25
Level 1 Cluster
22
Router
20
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
15
Level 4
Level 3
Level 2
Level 1
Level 0

FIG. 2

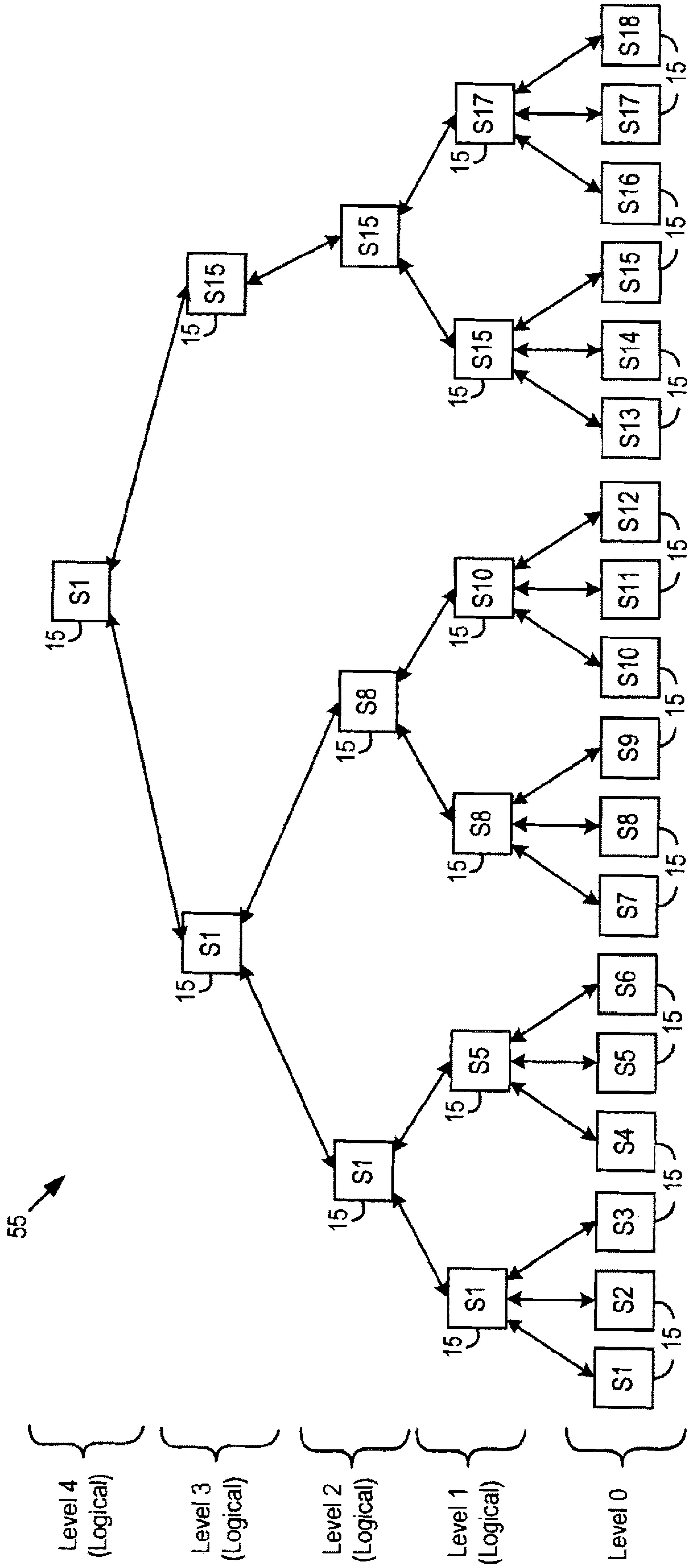

55
Level 4 (Logical)
Level 3 (Logical)
Level 2 (Logical)
Level 1 (Logical)
Level 0
S1
S15
S1
S15
S1
S8
S15
S1
S5
S8
S10
S15
S17
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
15

FIG. 3

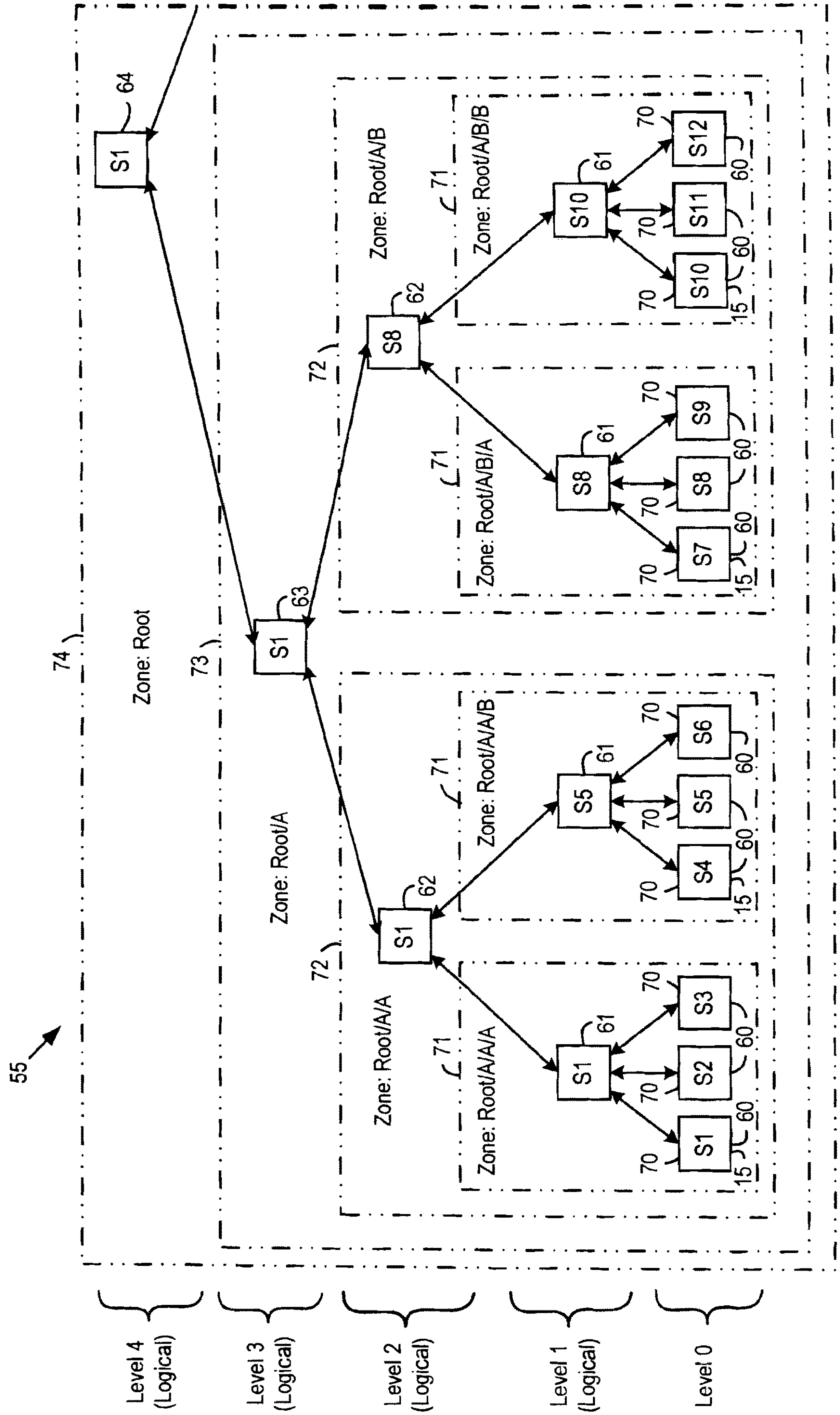

55
74
Zone: Root
S1
64
73
Zone: Root/A
S1
63
72
Zone: Root/A/A
S1
62
72
Zone: Root/A/B
S8
62
71
Zone: Root/A/A/A
71
Zone: Root/A/A/B
71
Zone: Root/A/B/A
71
Zone: Root/A/B/B
S1
S5
S8
S10
61
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
70
60
15
Level 4
(Logical)
Level 3
(Logical)
Level 2
(Logical)
Level 1
(Logical)
Level 0

FIG. 4

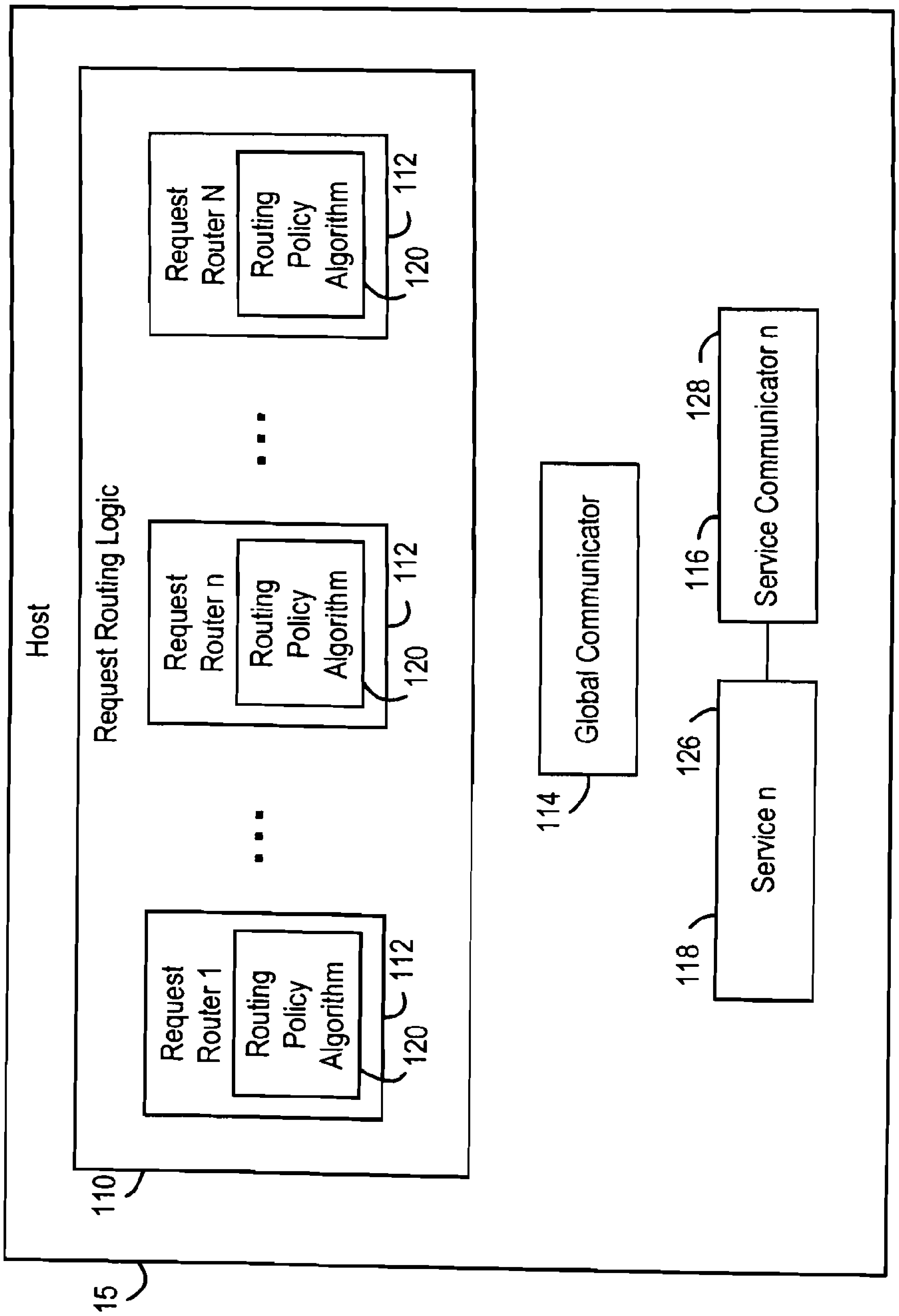
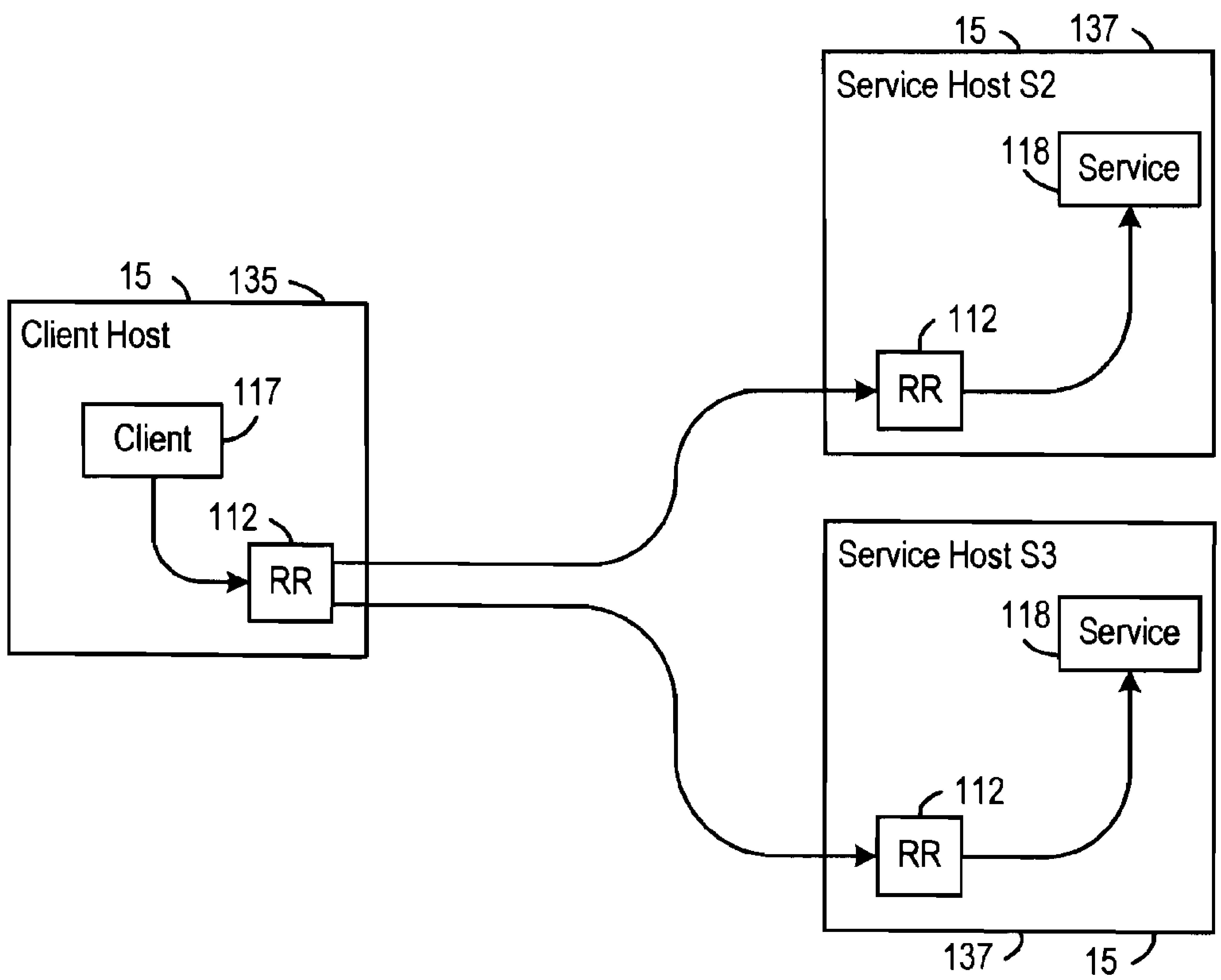

Host
Request Routing Logic
Request Router 1
Routing Policy Algorithm
Request Router n
Routing Policy Algorithm
Request Router N
Routing Policy Algorithm
Global Communicator
Service n
Service Communicator n
15
110
112
120
114
116
118
126
128

FIG. 5



15
135
Client Host
117
Client
112
RR
15
137
Service Host S2
118
Service
112
RR
Service Host S3
118
Service
112
RR
137
15

FIG. 6

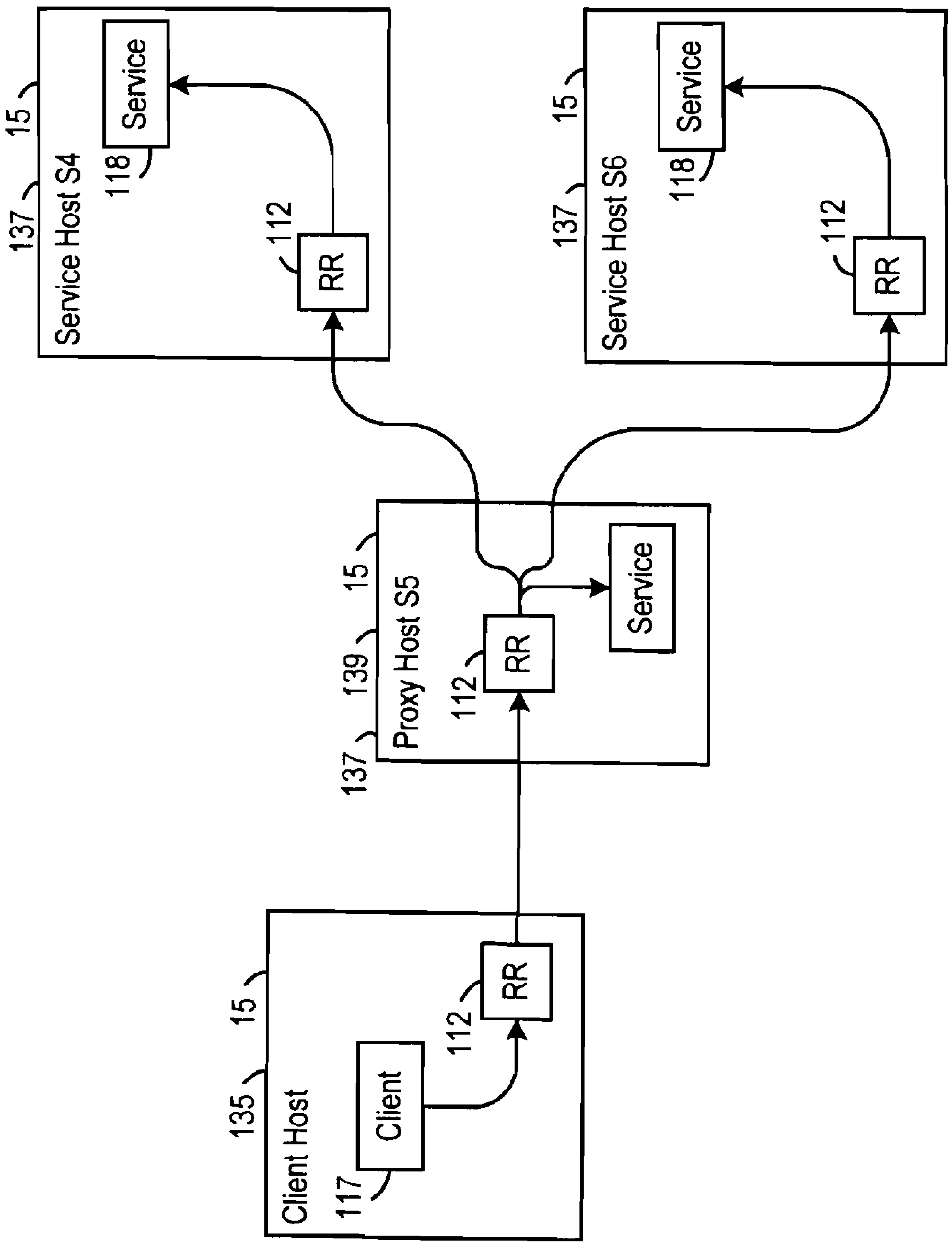

Service Host S4
137
15
Service
118
112
RR
Service Host S6
137
15
Service
118
112
RR
Proxy Host S5
137
139
15
112
RR
Service
Client Host
135
15
Client
117
112
RR

FIG. 7

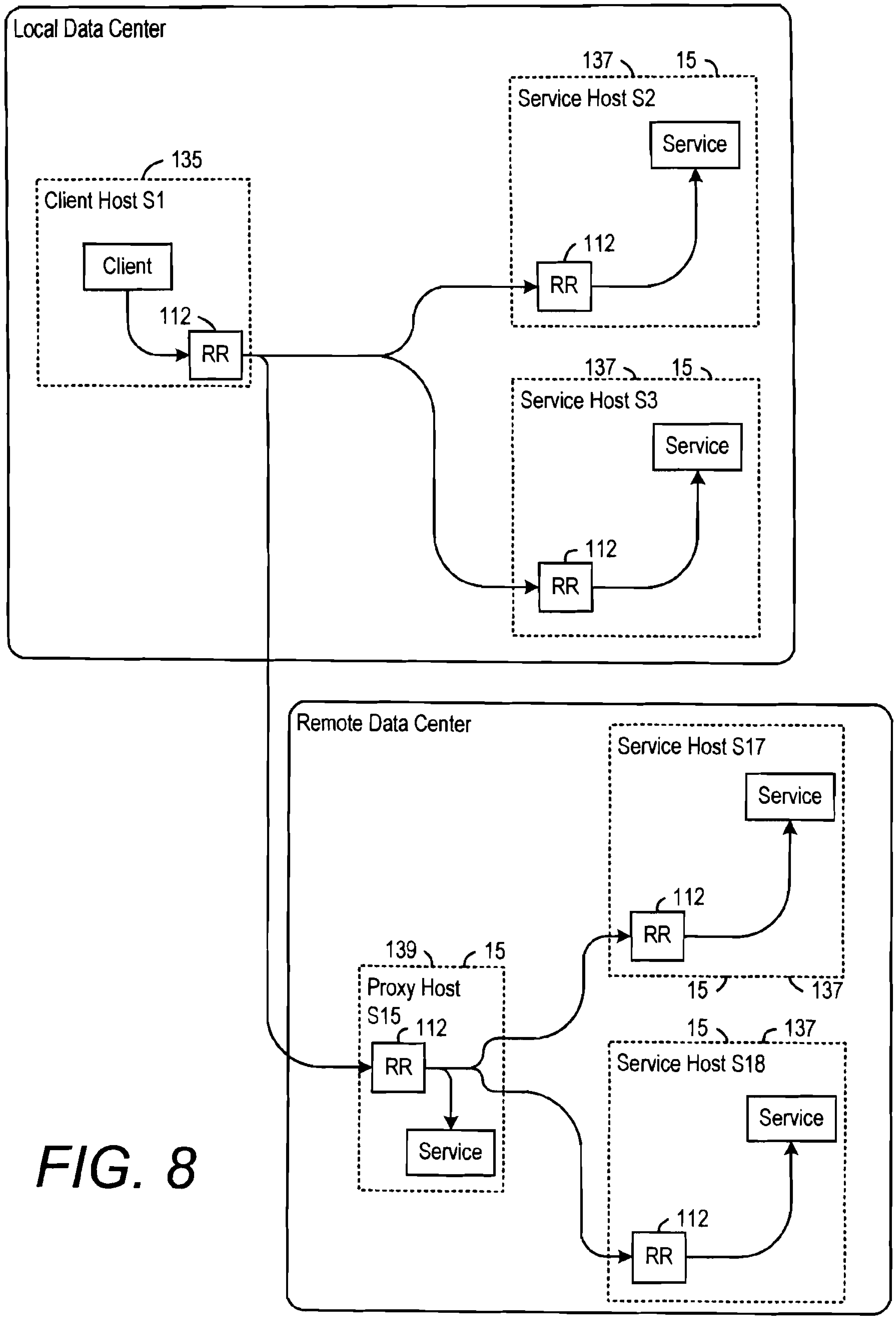
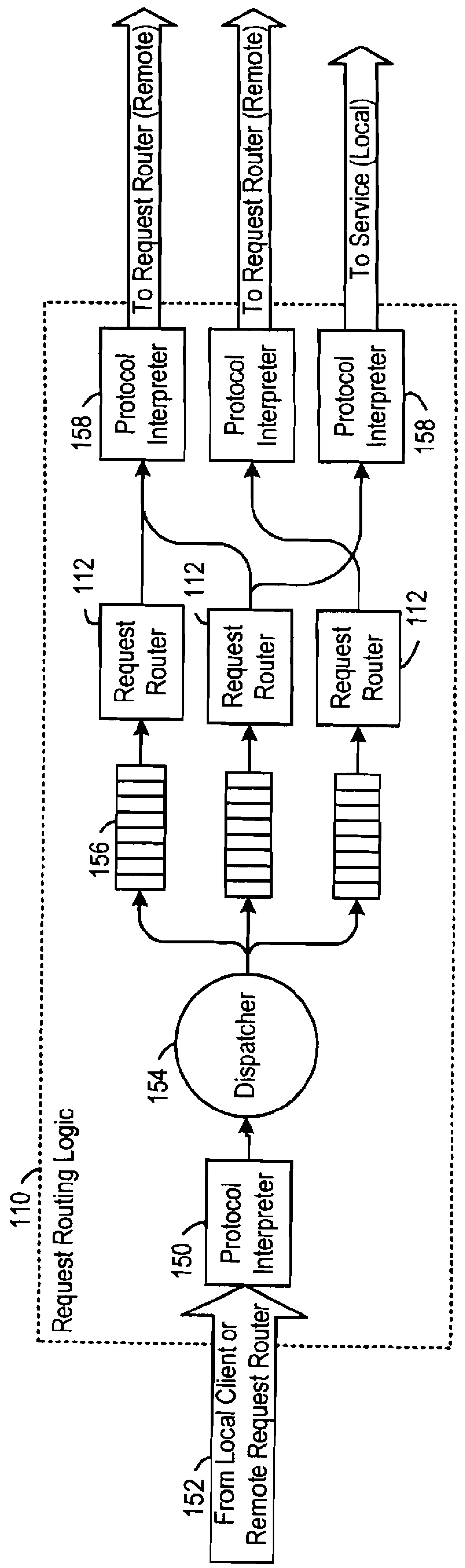

Local Data Center
137
15
Service Host S2
Service
135
Client Host S1
Client
112
RR
112
RR
137
15
Service Host S3
Service
112
RR
Remote Data Center
Service Host S17
Service
112
RR
139
15
Proxy Host
S15
112
RR
Service
15
137
15
137
Service Host S18
Service
112
RR

FIG. 8



110
Request Routing Logic
152
From Local Client or Remote Request Router
150
Protocol Interpreter
154
Dispatcher
156
112
Request Router
Request Router
Request Router
112
112
158
Protocol Interpreter
Protocol Interpreter
Protocol Interpreter
158
To Request Router (Remote)
To Request Router (Remote)
To Service (Local)

FIG. 9

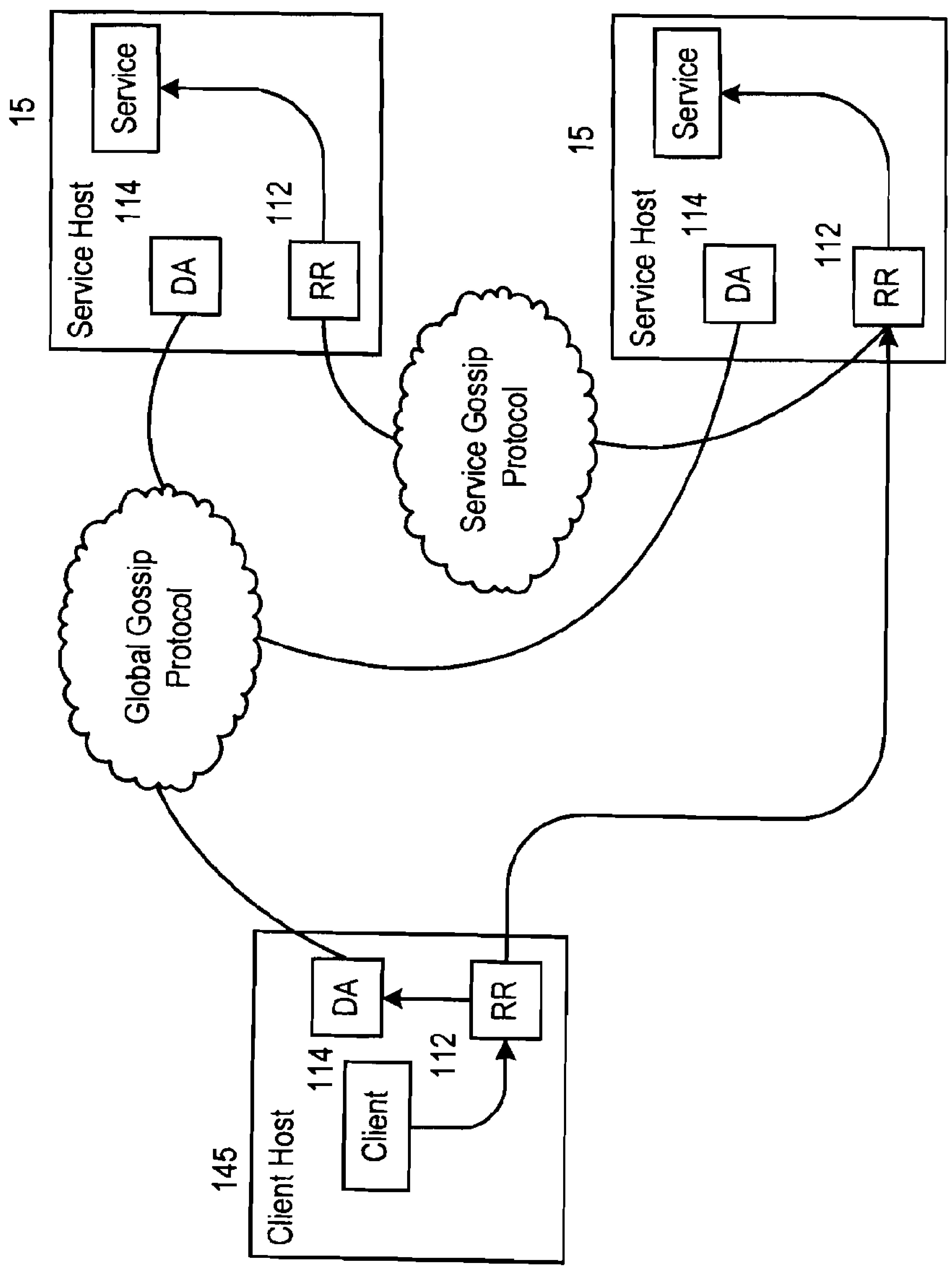
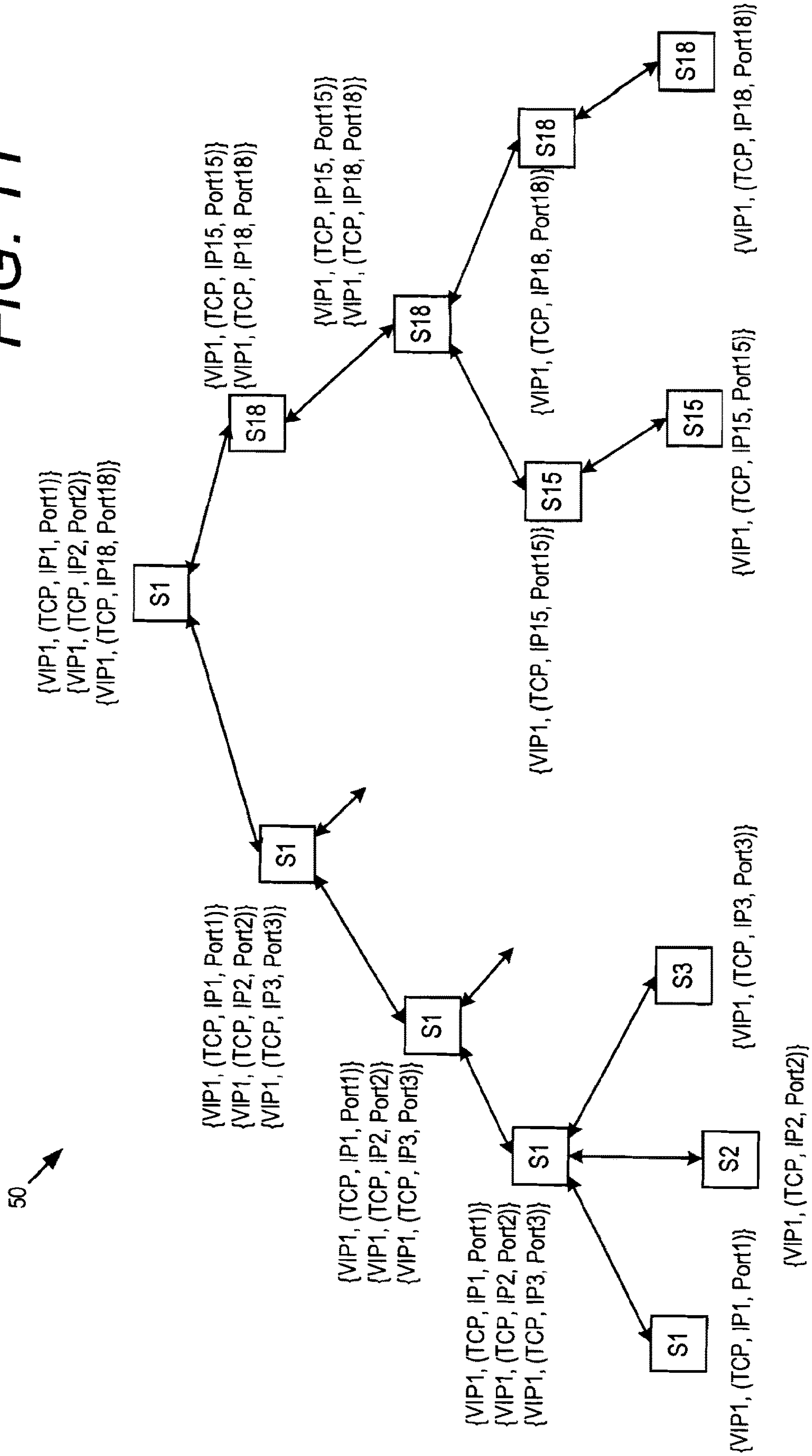

15
Service Host
114
DA
112
RR
Service
15
Service Host
114
DA
112
RR
Service
Service Gossip
Protocol
Global Gossip
Protocol
145
Client Host
114
DA
112
RR
Client

FIG. 10

FIG. 11


50
S1
{VIP1, (TCP, IP1, Port1)}
{VIP1, (TCP, IP2, Port2)}
{VIP1, (TCP, IP18, Port18)}
S18
{VIP1, (TCP, IP15, Port15)}
{VIP1, (TCP, IP18, Port18)}
S18
{VIP1, (TCP, IP15, Port15)}
{VIP1, (TCP, IP18, Port18)}
S18
{VIP1, (TCP, IP18, Port18)}
S18
{VIP1, (TCP, IP18, Port18)}
S15
{VIP1, (TCP, IP15, Port15)}
S15
{VIP1, (TCP, IP15, Port15)}
S1
{VIP1, (TCP, IP1, Port1)}
{VIP1, (TCP, IP2, Port2)}
{VIP1, (TCP, IP3, Port3)}
S1
{VIP1, (TCP, IP1, Port1)}
{VIP1, (TCP, IP2, Port2)}
{VIP1, (TCP, IP3, Port3)}
S1
{VIP1, (TCP, IP1, Port1)}
{VIP1, (TCP, IP2, Port2)}
{VIP1, (TCP, IP3, Port3)}
S1
{VIP1, (TCP, IP1, Port1)}
S2
{VIP1, (TCP, IP2, Port2)}
S3
{VIP1, (TCP, IP3, Port3)}

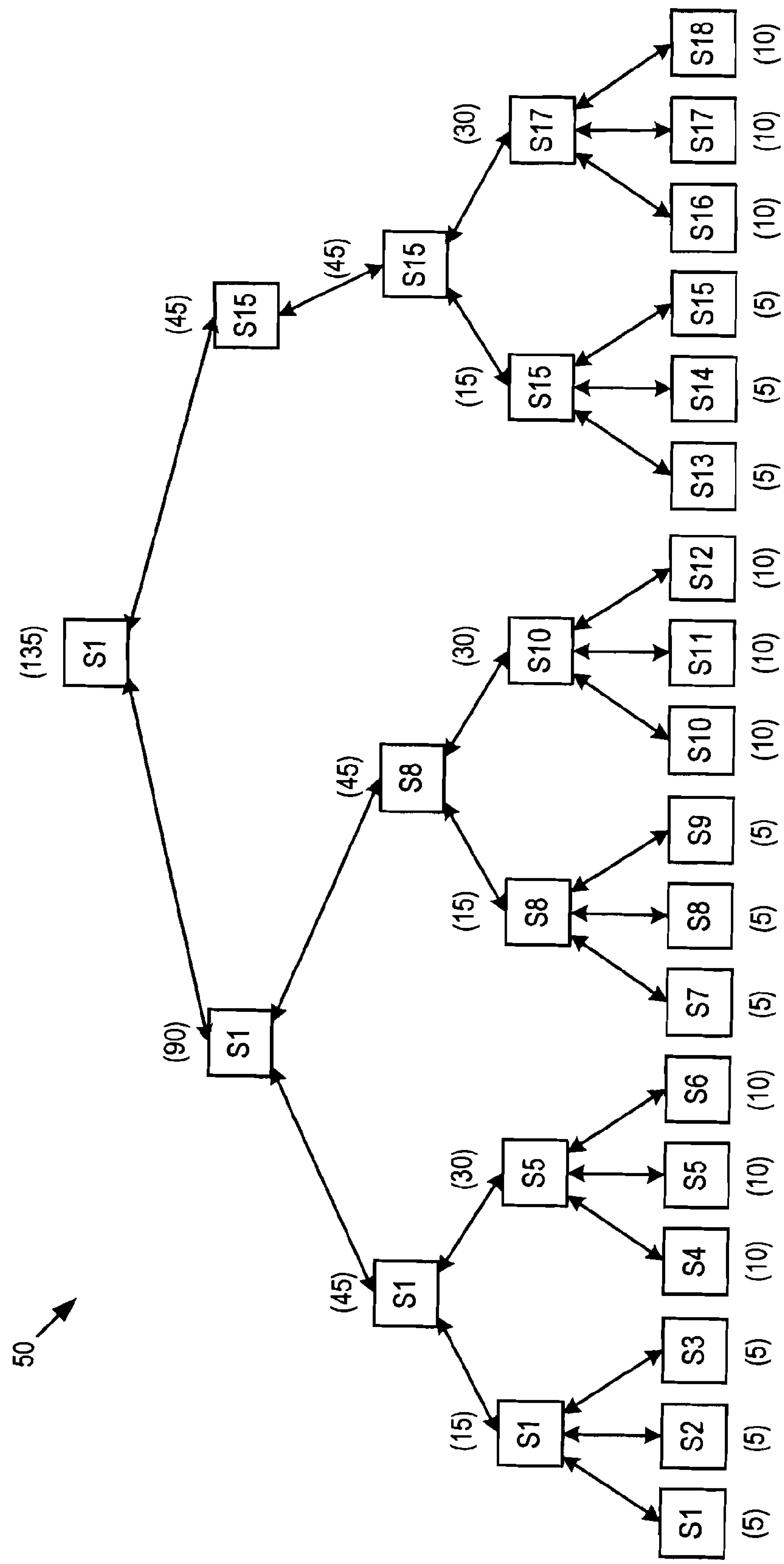

50
S1 (135)
S1 (90)
S15 (45)
S1 (45)
S8 (45)
S15 (45)
S1 (15)
S5 (30)
S8 (15)
S10 (30)
S15 (15)
S17 (30)
S1 (5)
S2 (5)
S3 (5)
S4 (10)
S5 (10)
S6 (10)
S7 (5)
S8 (5)
S9 (5)
S10 (10)
S11 (10)
S12 (10)
S13 (5)
S14 (5)
S15 (5)
S16 (10)
S17 (10)
S18 (10)

FIG. 12

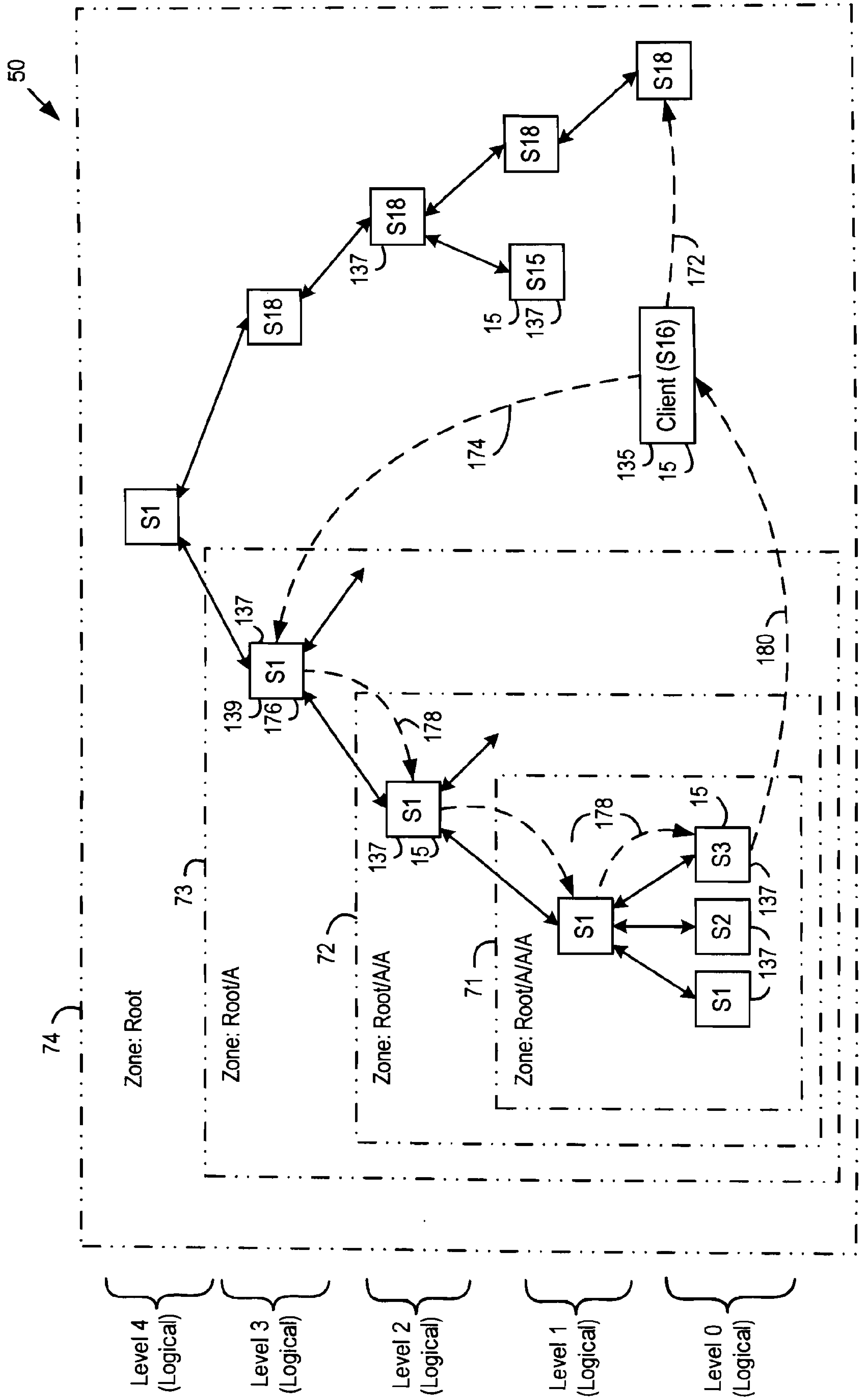

50
Zone: Root
Zone: Root/A
Zone: Root/A/A
Zone: Root/A/A/A
S1
S18
S15
S2
S3
Client (S16)
Level 4 (Logical)
Level 3 (Logical)
Level 2 (Logical)
Level 1 (Logical)
Level 0 (Logical)
71
72
73
74
15
135
137
139
172
174
176
178
180

FIG. 13

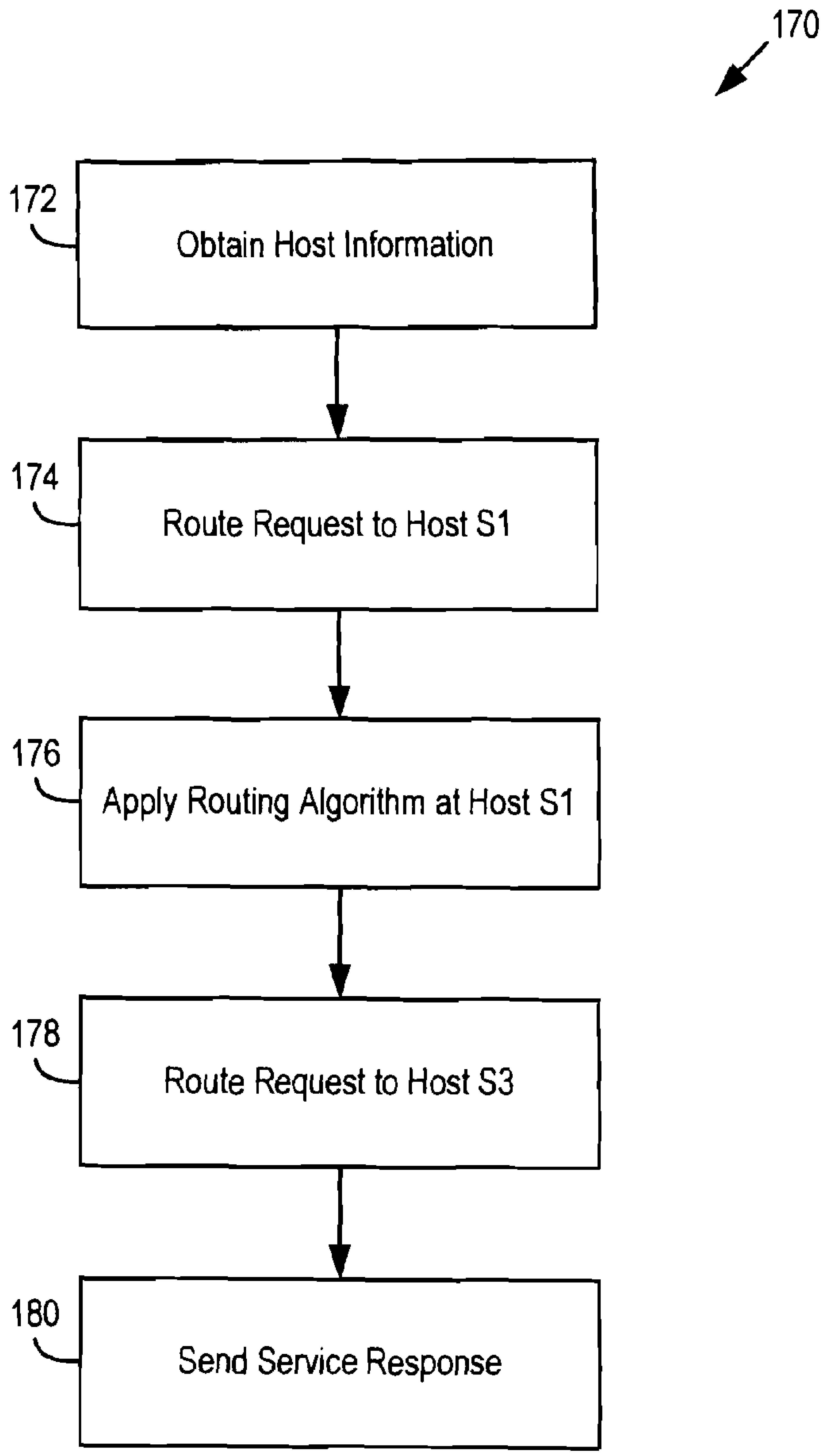

170
172
Obtain Host Information
174
Route Request to Host S1
176
Apply Routing Algorithm at Host S1
178
Route Request to Host S3
180
Send Service Response

FIG. 14

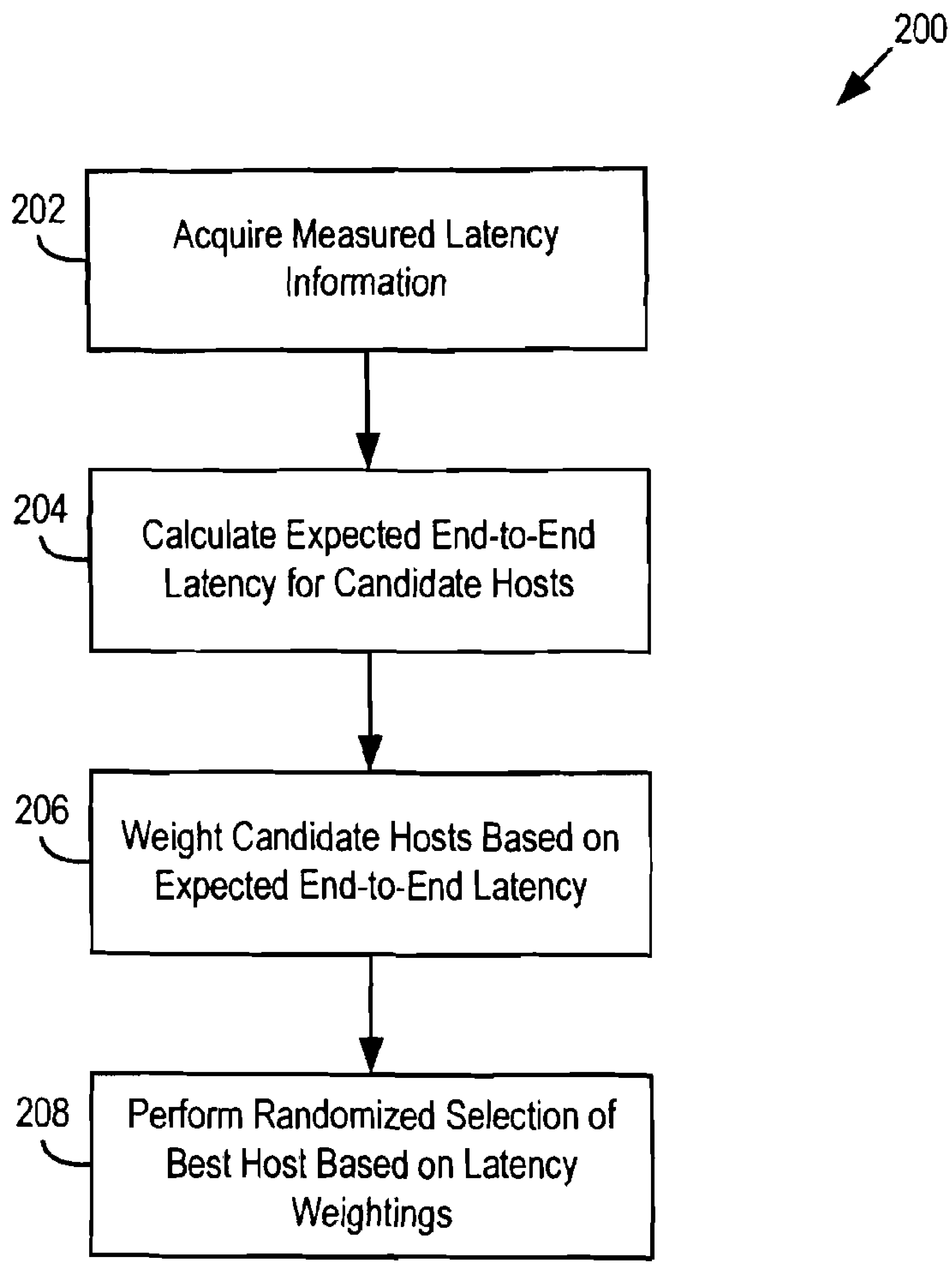

200
202
Acquire Measured Latency Information
204
Calculate Expected End-to-End Latency for Candidate Hosts
206
Weight Candidate Hosts Based on Expected End-to-End Latency
208
Perform Randomized Selection of Best Host Based on Latency Weightings

FIG. 15

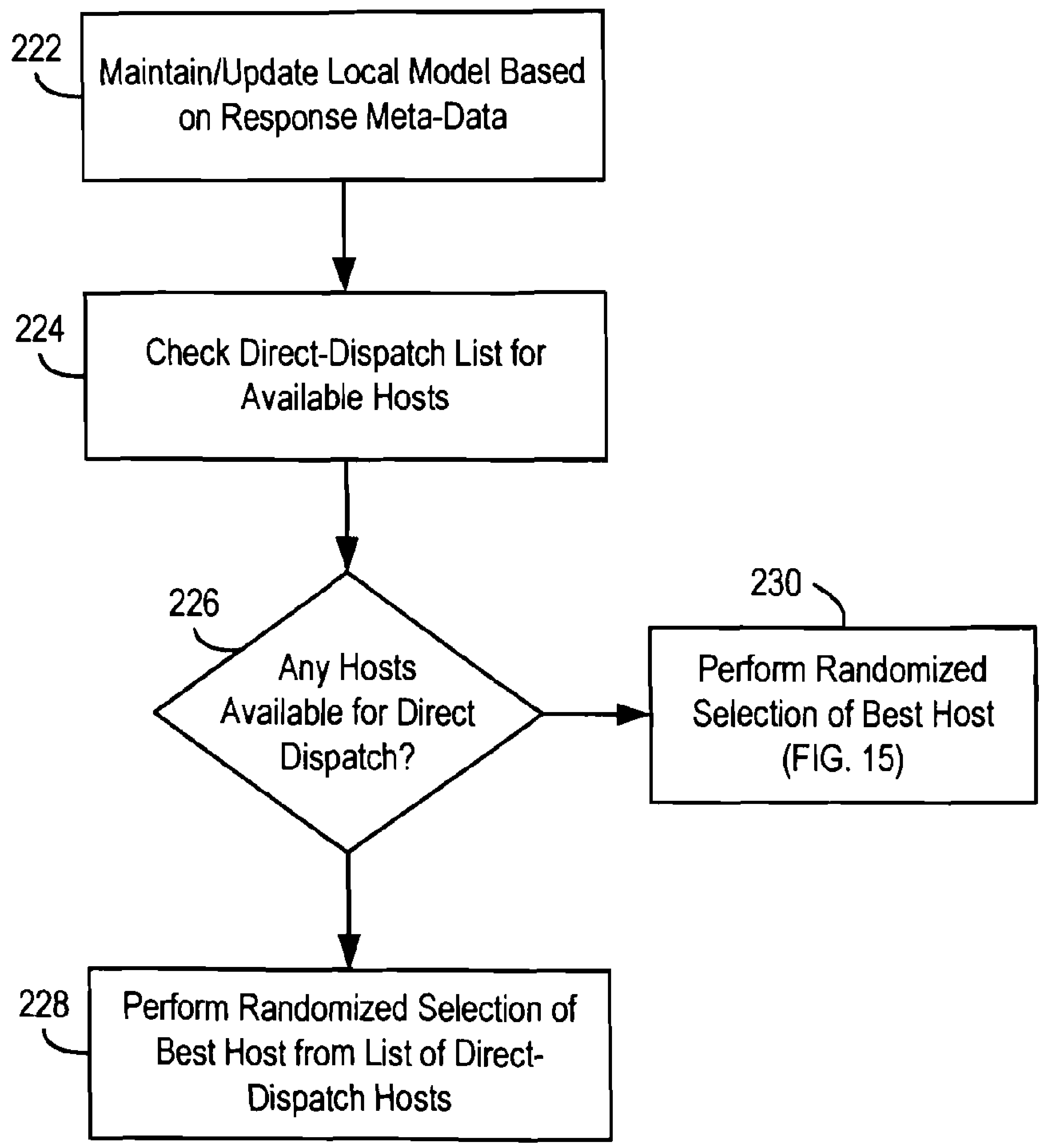

222
Maintain/Update Local Model Based on Response Meta-Data
224
Check Direct-Dispatch List for Available Hosts
226
Any Hosts Available for Direct Dispatch?
230
Perform Randomized Selection of Best Host (FIG. 15)
228
Perform Randomized Selection of Best Host from List of Direct-Dispatch Hosts

FIG. 16

SYSTEM AND METHOD FOR ROUTING SERVICE REQUESTS

BACKGROUND

Enterprise computing environments are often implemented in decentralized environments, both in terms of software structure and administrative organization, which use large numbers of low-cost server resources to meet processing requirements. For example, thousands of servers or more may operate across multiple data centers. The servers may host services (e.g., business logic applications) that are accessed by processes. To access a given service, a process may transmit a service request to the service and the service may generate a response which includes the requested information. To generate the response, the service may in turn transmit other service requests to other services and underlying data stores. There may be thousands of such services or more and each service may have multiple clients (e.g., other services) spread across the computing infrastructure. Often, services are replicated across multiple hosts in different data centers to improve their scaleability and availability. For example, a given service may be hosted in several different data centers in different geographic locations in order to avoid a single point of failure.

To manage such systems, it is desirable for a computing infrastructure to enable clients to discover services in a seamless way, route service requests to hosts in a reliable manner, and/or permit services to add capacity easily and transparently. Providing request routing systems that meet such goals has proven challenging, particularly in systems that may experience host failures and network partitions. However, meeting such goals may permit the business objectives of the computing infrastructure to be achieved more effectively and efficiently.

Accordingly, an ongoing need exists for improved systems and methods that may be used to route service requests. It should be noted that, while certain advantages and features are described, the teachings herein may be used to implement systems and methods that do not have any of the advantages and features, but rather which have other advantages and features.

SUMMARY

According to an exemplary embodiment, a computer-implemented method routes service requests to services in a service framework provided by a plurality of hosts. The method comprises receiving a service request for a service in the service framework and discovering a plurality of candidate hosts that host the service. The plurality of candidate hosts are a subset of the plurality of hosts. The method further comprises selecting a candidate host from the plurality of candidate hosts based on measured latencies for the plurality of candidate hosts and routing the service request to the selected candidate host.

According to an exemplary embodiment, a computer-implemented method routes service requests to services in a service framework. The method comprises storing a model of at least a portion of a hierarchically-organized computing environment that implements the service framework. The computing environment comprises a plurality of hosts. The model is organized in a hierarchy comprising (i) a first level including a plurality of leaf nodes, each of the leaf nodes corresponding to one of the plurality of hosts, and (ii) a second level including a first plurality of zones which each comprise a subset of the plurality of leaf nodes. The method further comprises dispatching service requests to different ones of the levels of the hierarchy based on measured latencies of the plurality of hosts.

It should be understood that the detailed description and specific examples, while indicating preferred embodiments of the present invention, are given by way of illustration and not limitation. Many modifications and changes within the scope of the present invention may be made without departing from the spirit thereof, and the invention includes all such modifications.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a hardware view of a system that employs a request routing system according to an exemplary embodiment;

FIG. **2** is a block diagram showing a portion of the system of FIG. **1** in greater detail;

FIG. **3** is a block diagram of a logical model of the system of FIG. **1** implemented by a request routing system according to an exemplary embodiment;

FIG. **4** is a block diagram showing a portion of the logical model of FIG. **3** in greater detail;

FIG. **5** is a block diagram of a host in the system of FIG. **3**;

FIG. **6** is a block diagram showing routing of a service request to one of multiple candidate hosts;

FIG. **7** is a block diagram showing routing of a service request to one of multiple candidate hosts through a proxy host;

FIG. **8** is a block diagram showing routing of a service request to one of multiple candidate hosts located in different data centers;

FIG. **9** is a block diagram showing request routing logic of the host of FIG. **5**;

FIG. **10** is a block diagram showing routing of a service request to one of multiple candidate hosts using a global communicator and a service communicator;

FIG. **11** shows operation of an aggregation function used to aggregate service contact information in the logical model of FIG. **3**,

FIG. **12** shows operation of an aggregation function used to aggregate node capacity information in the logical model of FIG. **3**;

FIG. **13** is a block diagram showing a client request being routed in a request routing system according to an exemplary embodiment;

FIG. **14** is a flowchart of the process shown in FIG. **13**;

FIG. **15** is a flowchart of a process for best host selection in connection with the process of FIG. **13**; and

FIG. **16** is a flowchart of a process for best host selection including a direct dispatch option in connection with the process of FIG. **13**.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

I. Exemplary Architecture

A. Physical Topology

Referring now to FIGS. **1-2**, a hardware system **10** that incorporates a request routing system **55** according to an exemplary embodiment is shown. FIG. **1** shows a physical topology of the hardware system **10**. The system **10** comprises a plurality of hosts (e.g., servers) **15**, a plurality of routers (e.g., switches) **20**, **25** and **30**, and a wide area network or other communication network **40**. In the example of FIG. **1**, the routers **30** are respectively located in different data centers, and the wide area network **40** connects hardware located in the two data centers. Although a limited number of hosts **15** and routers **20**, **25** and **30** are shown, it will be appreciated that the system **10** may, for example, comprise large numbers of servers (e.g., hundreds, thousands, millions, or more) operating across multiple data centers and hosting large numbers of services (e.g., hundreds, thousands, millions, or more). Each host **15** may include one or more client processes that may send service requests to one or more services **118** (see FIG. **5**) executing on other hosts **15**. Thus, any given host **15** may operate as a client host in some situations and as a server host in other situations. Herein, the term "client" is used to refer to internal processes hosted on the hosts **15** and not to external processes hosted on external computing systems, such as end user browsers in the case of a website application.

Each service **118** may be replicated across multiple hosts **15** to improve scaleability and availability. Further, each service **118** may be hosted in multiple data centers to avoid single point of failures (e.g., due to failure of a router **20**). When a client needs to make a service request, it may use a virtual IP address or other type of identifier for the service **118**, and the request may subsequently be routed to the service **118** as described in greater detail below.

By way of example, the system **10** may be used to host a website and/or to provide information to third parties that the third parties may use in hosting a website. For example, the system **10** may be used to host an interactive commerce website, a search engine website, content website, and/or other type of website. Various ones of the hosts **15** may be executing processes that are used to construct web pages and to publish the web pages to visitors of the website. Each web page may in turn be composed of results from multiple services **118**. Examples of services may include a product detail service, an ordering service, a shopping cart service, and so on.

As shown in FIG. **1**, the system **10** may be organized as a multi-level hierarchy comprising a plurality of levels, such as levels 0-4. Level 0 comprises the hosts **15**, which are individually labeled **S1**-**S18**. Level 1 comprises routers **20** that connect respective groups of the hosts **15**. Level 2 comprises routers **25** that connect respective ones of the routers **20**. Level 3 comprises routers **30** that connect respective ones of the routers **25**. Level 4 comprises a wide area network **40** that connects the routers **30**. At each level, different types of links may be used, such as high speed optical links, wide area networks, and so on, each with varying bandwidth and latency properties.

With reference to FIG. **2**, FIG. **2** shows a manner in which the hardware in Data Center **1** may be organized into a plurality of clusters **22**, **26**, and **32**. At level 1, each cluster **22** comprises one of the routers **20** and an associated group of the hosts **15**. At levels 2 and 3, each cluster **26**, **32** comprises one of the routers **25**, **30** which connects lower level clusters. The clusters **32** at level 3 correspond to a data center and multiple clusters **32** at level 3 may be connected through the wide area network **40**. By way of example, if it is assumed that a level 3 cluster corresponds physically to a data center, as described, then a level 2 cluster may correspond to an area within the data center, and a level 1 cluster may correspond to a rack of hosts **15** within the data center. Data Center **2** is not shown, however, it will be appreciated that the hardware in Data Center **2** may be grouped in a similar manner as shown for the hardware of Data Center **1**. Likewise, other data centers may be connected to wide area network **40**.

Given the physical topology as described above, the system **10** may have the following latency properties. First, the latency between hosts **15** in the same cluster may be lower than that of hosts **15** in different clusters. For example, within the same cluster **22** in level 1, the latency between hosts **15** may be very low as compared to the latency between hosts **15** in different clusters **22**. Second, the latency may increase at higher levels in the hierarchy. For example, latency between hosts **15** in different clusters **26** at level 2 is less than that of hosts **15** in different clusters **32** at level 3. As will be appreciated, the latency between two hosts **15** may be from microseconds or less to hundreds of milliseconds or more depending on whether the hosts **15** are in the same cluster (and at what level), whether they are in the same data center, the type of network connection(s) which connect the two hosts **15** (including the bandwidths and latencies of the network connection(s)), and so on.

B. Logical Model of Physical Topology

Referring now to FIGS. **3**-**4**, a logical model of the system **10** that is used by request routing system **55** is shown. The logical model depicted in FIGS. **3**-**4** is used by one or more communicators **114**, **116** (see FIG. **5**) that communicate information within the system **10** regarding contact information, availability, and so on, of services **118** in the system **10**. As shown in FIG. **3**, the hosts **15** may be organized in a logical hierarchy (tree structure). FIG. **3** shows the tree structure for both of the data centers shown in FIG. **1**. FIG. **4** shows the tree structure for the data center shown in FIG. **2**. As shown in FIG. **4**, the tree structure may comprise a plurality of nodes **60**-**64** and a plurality of zones **70**-**74**. The zones **70**-**74** are logical groupings of the nodes **60**-**64**. The nodes **60**-**64** each serve as representatives for a respective one of the zones **70**-**74**.

In an exemplary embodiment, the logical hierarchy in FIGS. **3**-**4** is configured to match the physical topology of the system **10**. In this embodiment, the nodes **60** which are at the bottom of the tree structure represent the physical hosts **15** in FIGS. **1**-**2**. The nodes **60** at the bottom of the tree structure are sometimes referred to herein as "leaf nodes." As shown in FIG. **1**, a cluster **22** at level 1 is formed by a subset of the hosts **15**. Likewise, zones **71**, **72** and **73** represent the clusters at levels 1, 2 and 3, respectively. Zone **74**, sometimes referred to herein as the "root zone," is a top-level zone and represents the entire set of clusters and underlying hosts **15** in FIGS. **1**-**2**. Zones **70**, sometimes referred to herein as the "leaf zones," correspond to individual hosts **15**.

The nodes **60**-**64** each serve as representatives for a respective one of the zones **70**-**74**. Thus, for example, host **S1** is the representative node **61** for the zone Root/A/A/A at level 1, the representative node **62** for the zone Root/A/A at level 2, the representative node **63** for the zone Root/A at level 3, and the representative node **64** for the root zone. The representative for each leaf zone is the corresponding host **15** itself. (Although not specifically shown, it will be appreciated that leaf zones **70** may also be designated in accordance with the above path-naming convention, e.g., Root/A/A/A/A corresponding to host **S1** at level 0). As will be described in greater detail below, the representative nodes **61**-**64** sometimes serve as intermediate proxies for routing service requests between the zones **70**-**74**. In this situation, the hosts **15** serving as the representative node are sometimes referred to herein as "proxy hosts." It may also be noted that the hosts **15** serving as representatives (which gossip information) need not necessarily the same as the hosts **15** serving as proxy servers (which route requests), because the two sets of hosts can be aggregated using different aggregation functions.

It may be noted that there is only one physical host (e.g., host **S1**), but it is represented at multiple levels in the tree structure. In practice, this may be implemented by having separate logical processes executing on the host **S1** for each separate zone **70-74** for which it is a representative node **60-64** (e.g., five separate logical processes for the arrangement shown in FIG. **1**). By designating a representative node at each level, it is not necessary for all nodes **60-64** to be gossiping with all of the other nodes **60-64** (e.g., to communicate status information as described below). Rather, the representative node may be responsible for gossiping with the sibling zones for a particular node **60-64**.

In the illustrated embodiment, there is one node **60-64** that serves as representative for each zone **70-74**. More generally, multiple hosts **15** may be designated as representative nodes for a given zone. For example, it may be desirable to designate two representative nodes, e.g., a primary representative and a secondary representative, such that the secondary representative may serve as a backup in the event of a failure of the primary representative. The representative set of nodes for a zone may comprise a subset of the nodes from lower-level child zones. To provide for robustness against network partitions and correlated failures, when designating representatives for zones, it may be desirable to choose hosts from different child zones, rather than too many from any single child zone. This approach may be used for both nodes **60-64** and intermediate proxy hosts **15**.

The groupings of nodes and zones may be determined by the groupings of hosts and routers in FIG. **1**, as shown. For example, the zone at level 4 may represent the entire system **10**, a zone at level 3 may correspond to a data center, a zone at level 2 may correspond to an area within the data center, and a zone at level 1 may correspond to a rack of hosts within the data center. As will be seen below, the fact that the logical hierarchy in FIGS. **3-4** is configured to match the physical topology of the system **10** makes the routing system **55** topology-aware. The fact that the routing system **55** is topology-aware permits network topology to be taken into account in routing decisions, e.g., by routing requests to hosts **15** that are topologically close to the clients. In another exemplary embodiment, the logical hierarchy in FIGS. **3-4** is not configured to match the physical topology of the system **10**, which may be useful in achieving other design goals in some applications.

C. Interconnection and Communication of Hosts through Request Routers and Communicators

Referring now to FIGS. **5-10**, FIG. **5** is a block diagram showing an exemplary host **15** in greater detail. FIGS. **6-10** are block diagrams showing more specific examples of the interconnection of multiple hosts **15** such as that shown in FIG. **5**.

Referring first to FIG. **5**, the host **15** comprises routing logic **110** including request routers **112**, one or more communicators **114**, **116**, and one or more services **118**. In an exemplary embodiment, as shown in FIG. **5**, the host **15** is shown as comprising only one service **118**. In other exemplary embodiments, a given server may host more than one service **118**.

The request routers **112** are each responsible for handling client requests, finding a set of candidate hosts that execute a requested service **118**, making a routing decision regarding the host **15** to which to dispatch a client request from among the set of candidates, and collecting client responses and dispatching them back to clients. Each request router **112** uses an associated routing policy algorithm **120** (described below) to route service requests from clients to one of the hosts **15** that executes the requested service **118**. In an exemplary embodiment, a separate request router **112** may be executing at each host **15** and for each different service **118**. Thus, the request routers **112** are labeled "Request Router **1**" to "Request Router N," where N is assumed to be the total number of different services **118** operating in system **10**. The request router **112** labeled "Request Router n" is assumed to be the request router associated with the n^{th} service, corresponding to the service **118** hosted on the particular host **15** illustrated in FIG. **5**. Because the request routers **112** are located with the hosts **15**, the decision-making regarding where to route service requests may be performed in a decentralized fashion avoiding single points of failure. Although FIG. **6** shows a separate request router **112** for each different service **118**, as will be appreciated, the individual request routers **112** within a given host **15** may also be combined into a single request router that provides request routing for multiple services **118**.

FIG. **6** shows the interconnection of hosts **15** through multiple request routers **112**. Thus, as shown in FIG. **5**, a client host **135** has a client process executing thereon which transmits a service request. The service request may be transmitted to service hosts **137**, which are assumed to host a common service **118**. The client host **135** and the service hosts **137** each include respective request routers **112**. On the client side, the request router **112** receives a service request from the client process **117**, finds a set of candidate hosts that execute the requested service **118** (e.g., hosts **S2**, and **S3** in FIG. **6**), and makes a routing decision regarding the host **15** to which to dispatch the client request from among the set of candidates. On the service side, the request routers **112** receive the service request from the request router **112** of the client host **135**, receive a response from the service **118**, and dispatch the response back to the client process **117**. Again, although only a single service **118** is shown in each of the hosts **15**, it will be appreciated that the hosts **15** may each be hosting multiple services **118** and/or multiple worker processes for each service **118**.

FIG. **7** is similar to FIG. **6** but the hosts **137** that execute the service **118** include a proxy host **139**. The proxy host **139** is disposed between the client host **135** and the remaining service hosts **137**. The proxy host **139** executes the same service **118** that is hosted by the remaining service hosts **137** and has the option of processing the service request locally or dispatching the service request to the remaining service hosts **137**, depending on the operation of the routing policy algorithm **120**. For example, in the illustrated embodiment, the proxy host **139** may be at level 1 and may have the option of processing the service request locally or dispatching the service request to either host **S2** or host **S3**, both of which are at level 0. FIG. **8** is similar to FIGS. **6** and **7** but shows an example in which service hosts **15** are located in different data centers. In FIG. **8**, the request router **112** of the client host **135** has knowledge of the local hosts **S2** and **S3**. The request router **112** also has the option of dispatching a service request to a proxy host **S15** located in a remote data center. The proxy host **S1** may then further dispatch the service request to lower level hosts, such as **S17** and **S18**, located in the remote data center.

FIG. **9** shows a request routing logic **110** in greater detail according to an exemplary embodiment. In an exemplary embodiment, all service requests processed by a particular host **15** (whether locally generated by a resident client process or remotely generated by a process executing on another host **15**) are processed by the request routing logic **110**. The request routing logic **110** includes an incoming protocol interpreter **150** which receives a stream **152** of incoming service requests from one or more local client processes and from request routers **112** of other hosts **15**. Each service request is parsed by the interpreter **150**, which may be configured to support multiple protocols (e.g., HTTP, TCP, XML, and so on). The service request is then provided to a dispatcher **154**, which stores information about registered services **118** such that service requests can be associated with a particular service queue **156**. Although only three queues are shown, it will be appreciated that if the system **10** has N different services **118**, then N different service queues **156** may be provided. The service queue **156** provides the service request to a request router **112** for a particular service **118** associated with the service request. The request router **112** selects the next routing hop for the service request, which may be for the service request to be sent to another host **15** or to a local process on the same host **15**. As shown in FIG. **8**, one of the request routers **112** has the option of routing service requests to a local service or routing the service request to the same service operating on a remote host **15**.

Referring again to FIG. **5**, the host **15** also comprises one or more communicators **114**, **116**. The communicators **114**, **116** communicate information between hosts **15**, including information regarding contact information for various services **118**, availability of services **118**, and so on, as described below. In an exemplary embodiment, the communicators **114**, **116** use a hierarchical gossip-based, peer-to-peer protocol. For example, the gossip protocol disclosed in the following patents, hereby incorporated by reference, may be used: U.S. Pat. No. 6,724,770, entitled "Multicast Protocol with Reduced Buffering Requirements," filed Feb. 17, 2000, U.S. Pat. No. 6,529,953, entitled "Scalable Computer Network Resource Monitoring and Location System," filed Dec. 17, 1999, U.S. Pat. No. 6,411,967, entitled "Distributed Processing System with Replicated Management Information Base," filed Jun. 18, 1999, and U.S. Pat. No. 6,134,244, entitled "Method and System for Optimizing Layered Communication Protocols," filed Aug. 28, 1998. The structure of the hierarchy for the hierarchical protocol may be in accordance with the discussion above in connection with FIGS. **3-4** for the physical infrastructure presented in FIGS. **1-2**. Due to the distributed manner in which all information is managed, the failure of any single network segment does not significantly impede the overall operability of system **10**.

In an exemplary embodiment, multiple communicators **114**, **116** are used. For example, a first (global) instance of the gossip protocol may be used by global communicator **114** to communicate information that is global and that is not limited in relevance to any particular service **118**, and additional (service) instances of the gossip protocol may be used by the service communicators **116** to communicate service-specific information that is limited in relevance to a respective service **118**. For example, a respective service communicator **116** may be used for each separate service **118**. The global communicator **114** and the service communicators **116** may be agents of the different instances of the above-mentioned hierarchical gossip protocol executing on a given host **15**. The use of separate communicators **114**, **116** allows more targeted communication to occur, i.e., such that a particular host **15** is not burdened with the communication overhead of communicating service-specific information that is not directly relevant to the operation of the particular host **15**. As will be appreciated, a single communicator may also be used which communicates both global and service-specific information.

The global communicator **114** may be configured to gossip about the entire set of services **118** and the hosts **15** that host them. The global communicator **114** aggregates information regarding the number of services **118** present in the system **10**, the number of hosts **15** executing a given service **118**, the contact information (e.g., IP address and port) for a small subset of hosts **15** of each service **118**, the number of clients accessing the service **118**, and so on. The global communicator **114** provides the dispatcher **154** (FIG. **9**) with information regarding registered services **118**.

Likewise, the service communicators **116** may each be respectively associated with one of the services **118** in system **10**. The service communicators **116** may also aggregate the contact information for a set of hosts **15** which act as intermediate proxies for routing requests. The proxies need not be the same as the nodes **60-64** in FIG. **3**, since they refer to the contact information (e.g., JP address and port) of the service communicators **116**, and may be aggregated by a different aggregation function. FIG. **10** shows a client host **135** communicating with hosts **15** using a discovery agent (global communicator) **114**, e.g., for purposes of service discovery. The service hosts **137** communicate with each other using service communicators **116**. The client host **135** does not participate in this communication. The global communicator **114** executes on all the hosts **15**, but the service communicator **116** is service-specific and only executes on hosts **15** hosting a particular service **118**.

The communicators **114**, **116** may be used to communicate global information and service-specific information between the hosts **15**, such that each host **15** is provided with information concerning at least some of the zones **70-74** in the tree structure of FIG. **4**. In an exemplary embodiment, each host **15** stores the state of all zones **70-74** on the path from its leaf zone **70** to the root zone **74** (including the root zone **74** itself). Further, each host **15** stores the state of sibling zones for all zones **70-74** on the path from its leaf zone **70** to the root zone **74**. For example, in the example shown in FIGS. **3-4**, node **51** knows about zones Root/A/A/A/B and Root/A/A/A/C (corresponding to hosts **S2** and **S3** at level 0), Root/A/A/B (at level 1), Root/A/B (at level 2), and Root/B (at level 3). However, **S1** does not know any child zones of Root/A/B (at level 2), nor of Root/B (at level 3). Limiting each host **15** to a subset view of the tree structure decreases the amount of data stored by each host **15**. Additionally, limiting each host **15** to a subset view of the tree structure also reduces the amount of data communicated over the network, thereby facilitating scalability.

Each of the nodes **60-64** may maintain their own status information and communicate the status information (i.e., using the communicators **114**, **116** of the respective host **15**) to higher level nodes for aggregation. The status information may be aggregated hierarchically, such that the zones **61-64** (i.e., the non-leaf zones) contain data aggregated from their respective child zones. Aggregated data may be used to give a summary of the system state to every participating node **60-64**. The use of aggregated data decreases the amount of data that each node **60-64** stores and communicates with other nodes **60-64**.

Referring now to FIGS. **11-12**, examples of the manner in which information may be aggregated is shown. In FIG. **11**, a manner in which contact information may be aggregated for the service communicators **116** is illustrated. Each host **15** publishes a tuple (e.g. {servicex.company.com, (TCP, 10.1.1.12, 9000)}), comprising a service name (e.g., SERVICEX) or Virtual IP (e.g., servicex.company.com) and a contact tuple, which in turn comprises a protocol (e.g., TCP), an IP address (e.g., 10.1.1.12) and a port (e.g., 9000), into its local state. For each upper level zone **71-74**, the contact information for the services **118** in the zones **70-73**, respectively, in the immediately lower level (the zone children) is then aggregated. Since aggregation is recursive, the root node **64** ultimately identifies all the services **118** available in system **10**. In FIG. **11**, the aggregation includes a bounding function which limits the number of contacts to an upper bound (e.g., three contacts per zone, in the illustrated example). The use of a bounding function in this manner reduces the amount of information that is aggregated as the number of hosts increases, thereby enhancing scaleability. As will be appreciated, a variety of factors may be used to select which hosts **15** are deleted from the contact information during aggregation, such as performance metrics and whether any other hosts **15** from the same zone are already included in the bounded contact list. Any information that is used for host selection during aggregation may be included in the information that is aggregated. The same process may also be used to aggregate other types of information using other aggregation functions, such as latency information or capacity information. For example, in FIG. **12**, the process may be used to aggregate capacity information using the function sum( ), which returns the sum of the capacity from among the zone children. For each upper level zone **71-74**, the capacities of the zones **70-73**, respectively, in the immediately lower level (the zone children) may be aggregated. Since aggregation is recursive, the root node **64** ultimately contains the total capacity of all hosts **15**. For example, the capacity of each host **15** (at level 0) S**1**, S**2**, and S**3** is 5, the aggregated value of their parent zone (at level 1) is 15. The aggregation function may be configured such that double counting is avoided, that is, so that the capacity of host S**1** is not counted both at level 0 and at level 1. It may be noted that even if the same host **15** acts as a proxy in different zones, it may behave differently based on the zone it represents. For example, the total capacity represented by host S**1** at level 2 is the sum of the capacities of hosts S**1**, S**2**, S**3** and whatever is represented by host S**5** at level 1. However, the capacity of host S**1** at level 1 is only the sum of hosts S**1**, S**2** and S**3**. After the aggregation function is applied to all the other zones, the capacity of the root node **64** is 135, as shown. Data may be aggregated using substantially arbitrary aggregation functions, which may be dynamically inserted into the system, removed, and modified.

The states of different hosts **15** may be kept eventually consistent using a series of gossip protocol instances, for example, one for each level in the tree structure. The gossip protocol may use point-to-point messages and take into account network boundaries, e.g., switches and routers. The gossip protocol may minimize communication across boundaries by gossiping less frequently to far zones. Aggregating information and minimizing communication across boundaries helps keep bandwidth consumption low. In an exemplary embodiment, the routing system **55** also maintains an eventually consistent membership protocol using a gossip failure detection arrangement, as known in the art. An example of such an arrangement is disclosed, for example, in R. van Renesse, Y. Minsky, and M. Hayden, "A gossip-style failure detection service," Technical Report TR98-1687, 28, 1998.

In an exemplary embodiment, multicasting may be used for initial discovery, e.g., to permit hosts **15** to discover each other. The network infrastructure for the system **10** may support multicasting to a group that corresponds to each zone in the network topology, i.e., one group for a level 1 cluster, one group for a data center, and so on. Hosts **15** (nodes **60-64**) may periodically multicast on a scoped multicast address at every level in the tree structure. In an exemplary embodiment, in order to reduce multicast traffic, each host **15** multicasts at a particular level only once per period with a probability inversely proportional to the number of nodes at that level. Hence, on the average, only one host multicasts per discovery period at each level.

In an exemplary embodiment, service advertisement may be achieved through automated registration. For example, at startup, each service **118** may register with its local request router **112** (i.e., the request router **112** on the host **15** upon which the service **118** is executing). The request router **112** may then use the global communicator **114** to locate and connect to the gossip protocol instance for the service **118** (or create a new one, if necessary). Clients may then be permitted to find services **118** and hosts **15** transparently using the service name (e.g., virtual IP address). In the event of a failure of the service **118**, its registration may be removed from the information that is obtained through aggregation. Additionally, in the event of a failure of the host **15**, the registration of the service **118** is automatically removed. This is because the host **15** is responsible for writing its own local state and, without the host **15** to write its local state, the information is not included in the information that is aggregated on other hosts **15**. Thus, there is no need for deregistration in case of failure of a service **118** or host **115**. This arrangement avoids the need to manually configure clients with service-specific configuration information, such as hard coded IP addresses of services **118**. This arrangement also avoids the need for explicit registration of services **118** with a central registration entity, which in turn promotes decentralized system administration. Furthermore, since the state for each node **60-64** is writable only by the node itself, a misconfiguration of one node will not affect other nodes.

II. Service Discovery and Host Selection

The routing system **55** divides the problem of finding the best host **15** (that executes the requested service **118**) to which to route a request into two subproblems: (i) service discovery (i.e., discovering the candidate set of hosts that host a given service), and (ii) best host selection (i.e., selection of the best host among them to serve the client request). An exemplary service discovery and request routing process is described in Section II(A) below in connection with FIGS. **13-14**. Exemplary procedures for selecting a best host during the request routing process of FIGS. **13-14***e* are described in Section II(B) below.

A. Exemplary Service Discovery and Request Routing Process

In an exemplary embodiment, service discovery and host selection are performed in a decentralized fashion using the global communicators **114** and service communicators **116** of the various hosts **15**. Using this arrangement, a client host **135** finds the set of hosts **137** that together execute a given requested service **118**. Subsequently, the client host **135** executes its own request router **112** to select the best host **137** to which to dispatch its request. A service host **137** that receives the client request may process the request locally or may forward the request to another service host **137** (thereby acting as an intermediate proxy host **139**, as in FIG. **7**). This decision is made by the request router **112** of the service host **137** based on the associated routing algorithm **120**.

Referring now to FIGS. **13-14**, FIGS. **13-14** show this process in greater detail. When a client process initiates its first request to a service **118**, the service request is received by a request router **112** of the client host **135**. At step **172**, the request router **112** of the client host **135** discovers information about the service **118**. Particularly, the request router **112** uses its global communicator **114** to find the nearest contact hosts **137** of the service **118**, where "nearest" refers to the service host **137** that is the fewest number of network hops away. Subsequently, the request router **112** of the client host **135** connects to the service communicator **116** of the service host **137** and downloads information regarding the set of hosts **137** that host the service **118** (i.e., that host's view of the tree structure for the respective service **118**). In the example given in FIG. **12**, if a client host **135** connects to host S**18**, the list of candidate service hosts **137** it learns about is host S**18** (at level 0), hosts S**15** and S**18** (at level 1), host S**18** (at level 2), hosts S**1** and S**18** (at level 3), and host S**1** (at the root level). As described above in connection with FIGS. **3-4**, each host **15** stores the state of all zones **70-74** on the path from the respective leaf node to the root node, as well as their sibling zones. In the illustrated example, the client host **135** may, for example, be host **816** in FIG. **3**, resulting in S**18** being the topologically closest host.

At step **174**, once the request router **112** of the client host **135** receives the list of candidate hosts **137** from the service communicator **116**, the request router **112** of the client host **135** selects the best host **137** to which to dispatch the given request and dispatches the service request to the selected host **137**. As indicated above, in some embodiments, the zones **70-74** may have multiple designated representative nodes, e.g., a primary representative and a secondary representative. In such circumstances, the logical point of dispatch may be the respective zone **70-74** rather than any individual host **137**.

At step **176**, the service request is received by the request router of the selected host **137**. Once the service request is received, the request router **112** of the selected host **137** has two options: (1) it can handle the service request locally, or (2) it can forward the service request to another node at a lower level. Even though it is desirable for hosts **15** to handle all requests locally, this can lead to overloading of the hosts. Hence, each request router **112** may be configured to perform a proper balancing between serving requests locally and forwarding the service requests to other hosts **137**. Additionally, when the service request is forwarded to another host **137**, if the first server **137** is more heavily loaded than the second server **137**, then the end-to-end latency of the response to the service request may be reduced. This balancing may be performed using the routing algorithm **120**, described in greater detail below.

In the example of FIGS. **13-14**, the outcome of the routing algorithm at step **176** is shown to be that the service request is forwarded to another node at a lower level. Accordingly, at step **178**, the service request is forwarded to the host S**1** at level 2. In the event of the request being forwarded to another node, the system **10** may be configured to ensure that routing loops do not occur by requiring that service requests are always forwarded to a zone deeper in the sub-tree of the zone to which it was addressed. Service requests entering the request router **112** of the root node **64** are logically directed to the root zone **74**, thus that service request can be routed anywhere in the tree structure. For example, in FIG. **13**, host S**1** can route to host **52** only if it receives a service request logically directed to level 1 or higher. On the other hand, if host S**1** receives a request directed to it at level 0, then the service request is processed locally. Thus, in FIG. **13**, the first two routing hops are from host S**1** at level 3 to host S**1** at level 2, and from host S**1** at level 2 to host S**1** at level 1, respectively. In other words, the service request is routed to the host S**1**, but is logically routed to lower levels in the tree structure. Thereafter, the next routing hop is from host S**1** at level 1 to host S**3** at level 0. Although not explicitly shown in FIG. **14**, it will be appreciated that the request router **112** of a respective node applies its respective routing algorithm **120** as described above in connection with step **174** for each routing hop in the tree structure.

At step **178**, the service request is routed to the service host S3, where it is ultimately serviced. The response to the service request is then returned to the client host **135** at step **180**. When the response is finally returned, the response may be sent through a path which is different from the routing path through which the service request came. For example, the request router **112** of the service host **137** may send the response directly to the request router **112** of the client host **135** (e.g., via a TCP connection). On the return path, it is not necessary to engage in best host selection since the destination host for the response (i.e., client host **135**) is known. This avoids incurring additional routing overhead and reduces the end-to-end latency of the request.

In an exemplary embodiment, after the process depicted in FIGS. **13-14** has been performed once by a client host **135** with respect to a specific service **118** (i.e., after the first service request to the service has been initiated and a response has been received), the client host **135** may register itself as a listener to the gossip protocol instance associated with the service communicator **116**. This permits the client host **135** to receive a continuous stream of updates regarding the state of the service **118**. For example, in FIG. **13**, the host S**18** may communicate changes to the service tree structure to the client host **135** as the changes occur by way of a direct connection (e.g., a TCP connection which is kept open). By registering itself as a listener, the client host **135** obtains updates for services **118** in which it is interested. In subsequent repetitions of the process **170** shown in FIGS. **13-14**, the client host **135** may therefore skip the step of discovering information about the service **188** (step **172**), and proceed directly to step **174**. Also, because the client host **135** is only registered as a listener, the client host **135** does not need to execute additional instances of the service communicator **116**, which may otherwise increase the load on the client host **135**. Given that some hosts **15** in system **10** may access many services **118**, avoiding the additional overhead of executing additional instances of the service communicator **116** may be desirable.

B. Routing Policy

1. Latency-Aware Dispatch

The routing algorithm **120** is responsible for selecting the best host **137** to service a service request from a candidate set of service hosts **137**. In an exemplary embodiment, the routing algorithm **120** selects the best host **137** using an approach that reduces average end-to-end service latency for client service requests.

Particularly, in an exemplary embodiment, the routing algorithm **120** uses a randomized (i.e., pseudo-randomized), latency-aware dispatch policy in which zones are weighted based on their expected end-to-end latency. For example, if $\overline{lat}=\{lat_1, lat_2, \ldots, lat_n\}$ is the vector of expected latencies when sending a request to a candidate set of zones ($Z_1 \ldots Z_n$), then

$$p_i = \frac{\frac{1}{lat_i}}{\sum_{j=1}^{n} \frac{1}{lat_j}} \tag{1}$$

where p_i is the probability of dispatch to a zone Z_i. As will be appreciated, zones are logical groupings of hosts **15** and are treated as entities unto themselves merely for purposes of performing calculations in connection with the latency aware dispatch policy. Requests logically dispatched to zones and are physically dispatched to hosts.

From Eq. (1), it follows that the probability of dispatch to any particular zone Z_i within a candidate set of zones is inversely proportional to the expected end-to-end latency when sending the service request to the particular zone Z_i. For example, if there are two candidate zones Z_1 and Z_2, and if the two candidate zones Z_1 and Z_2 have relative latencies of 5 and 10, then the randomized strategy may dispatch a service request to zones Z_1 and Z_2 with a probability of 0.67 and 0.33, respectively.

The expected end-to-end latency values lat_i for a request from a client host C_j when served by zone Z_i at level 1 are computed based on Eq. (2) as follows:

$$lat_{ij}=NL_{ij}+RL_i+SL_i(l) \tag{2}$$

where

(i) NL_{ij} is the Network Latency, that is, the time incurred by the request in traveling through the network from the client (C_j) to the zone (Z_i) (e.g., if a network has higher latency properties than this latency is higher);

(ii) RL_i is the Redirection Latency, that is, the time incurred due to redirection overheads (e.g., if a request travels through multiple request routers **112**, then this latency is higher); and,

(iii) SL_i is the Service Latency, that is, the time taken by a zone to execute a given service request. The Service Latency includes both the time taken by the service **118** to execute the service request (which depends on the processing power of the hosts **137** within the zone) and the time spent by the service request in the queue of the host **137** waiting to be serviced.

It may be noted that the expected service latency $SL_i(l)$ for a zone is dependent on the level of the zone. The reasons for this is as follows: If the zone is at a higher level, then its service latency is the weighted average of the time the request will take to execute when forwarded to its children, including the Network Latency. For example, the service latency $SL_1(\mathbf{0})$ of a zone at level 0 is just its own measured service latency. On the other hand, the service latency $SL_1(1)$ of a zone at level 1 is the weighted average of $SL_1(0)$, $(NL_{1,2}+RL_2+SL_2(0))$, and $(NL_{1,3}+RL_3+SL_3(0))$, where NL_{ij} is the Network Latency from zone Z_i to zone Z_j as measured by zone Z_i. It may be noted that, in the example given in FIG. **13**, Network Latency for host S**3** at level 0 is 0, since the dispatch is to a process executing within the host S**3**.

By performing routing based on measured latency, as in Eq. (2), the routing algorithm **120** is configured to be dynamic and adaptive (i.e., it adapts to changes in the load of individual hosts **15**). For example, if the service hosts **137** within a zone become heavily loaded, the service latency SL_i for the zone increases, decreasing the probability that subsequent service requests will be routed to the zone (i.e., until it becomes less heavily loaded). Likewise, the routing algorithm **120** is able to adapt to changes in client request rate and the addition/removal of new service hosts **137** executing a particular service **118**. The routing algorithm **120** is also configuration independent, since it relies on end-to-end latency, which may be compared in straightforward manner between zones, and does not rely on any manually configured parameters (e.g., hosts' relative processing capacity and memory capacity) to make routing decisions. Different relative processing capacities and memory capacities are reflected in measured service latencies, causing zones with less powerful hosts **135** to receive fewer service requests when their service latencies rise above the service latencies of other service hosts **137**. By also taking into account the network latency NL_{ij}, the routing algorithm **120** is also able to take into account different parts of the networking infrastructure of system **10** which may have different bandwidth and latency characteristics. This avoids high latencies if the hosts **15** are spread across different data centers, especially in a WAN environment. Thus, heterogeneity in host resources and networking capabilities is taken into account.

By focusing on end-to-end latency rather than evenness of workload sharing, response time for client hosts **135** may also be improved. A given host **137** may be selected based on minimization of end-to-end latency, even though selection of the host **137** results in uneven load distribution among hosts. For example, if there are two candidate hosts **137**, one of which is lightly loaded but in a remote data center, the closest host **137** may be selected if doing so is likely to result in a lower overall end-to-end latency. The closest host **137** may be selected even though it may already be more heavily loaded than the service host **137** in the remote data center.

Additionally, as previously indicated in connection with Eq. (1), the dispatch strategy used by the routing algorithm **120** is a randomized strategy. A randomized dispatch strategy avoids a "herd effect" that may be encountered when dispatching requests to a host that is perceived to be the least loaded, particularly in situations where the load/latency information the clients are operating on is stale. In such situations, the host that appears to be under-utilized may become quickly overloaded, and then the "herd" stampedes another host, and so on. A randomized dispatch strategy avoids the dispatching of all service requests to any one (least-loaded) host but, rather, dispatches service requests to multiple hosts including more heavily-loaded hosts (albeit with a lower probability than the less heavily loaded hosts). In the exemplary embodiment described above, the routing algorithm **120** uses a latency-based randomized dispatch strategy in which the weighting coefficients for the randomized dispatch are determined based on measured latencies. In other exemplary embodiments, the weighting coefficients for the randomized dispatch may be determined based on other parameters, such as the relative capacities of the hosts **137**. For example, if zones $Z_1, Z_2, \ldots Z_n$ is the list of zones known by a request router **112**, and $c_1, c_2, \ldots c_n$ are their respective advertised capacity, then each request router **112** may compute a set $P=p_1, p_2, \ldots, p_n$, which will be the probabilities of routing to each of these zones, such that $p_i=c_i/\Sigma_{j-1}^{n} c_j$. The capacity, for example, may be the number of processes executing the relevant service **118**, properly calibrated to take into account the capabilities (e.g., CPU, memory, IO bandwidth, and so on) of hosts within the zone.

Additionally, in the exemplary embodiment, both the service discovery and routing decisions occur at individual hosts **15**. Service discovery and routing decisions are therefore decentralized, permitting the routing system **55** to avoid a single point of failure, both in terms of hosts **15** and network segments. Likewise, as previously described, service registration may also be performed in a decentralized manner.

Referring now to FIG. **15**, FIG. **15** is a flowchart showing a process **200** for best host selection. The process **200** may, for example, be implemented in connection with each of the routing hops described above in connection steps **134-136** of FIGS. **13-14** and may incorporate the randomized dispatch technique described above in connection with Eqs. (1)-(2).

As indicated above, requests are logically dispatched to zones and physically dispatched to hosts. Accordingly, although in some instances reference is made to hosts **137**, it will be appreciated that the dispatch policy described above relative to zones is also applicable to the discussion of FIG. **15**.

At step **202**, latency information is acquired from the service hosts **137**. The service latency may be first learned through aggregation functions as discussed above in connection with FIG. **12**, and subsequently through information received as responses to service requests are routed to the client host **135**. Initially, for example, in the absence of feedback, all request routers **112** may start with equal dispatch probabilities for their next hop. Then, during request routing, each host **137** in the routing path may append the average SLi and RLi for the service hosts **137** in their sub-trees, i.e., from those to which they dispatched requests. This information may be used to update the information base in the client host **135**. For example, in FIG. **13**, if host S3 receives a service request from a client host **135** through the path (S**18**, S**1**, S**3**), the reply may be sent back to the request router **112** of the client host **135** directly. However, the host S**3** may send aggregated completion notifications to host S**1** which in turn may send notification to host S**18**, and so on, through the path (S3, S1, S**18**). Host S**1** may put the values of RL_1, S**1**(**3**), S**1**(**2**), and S**1**(**1**) in the metadata, and this information may be used to update the information in the request router **112** in the client host **135**. Each request router **112** may transmit a completion notification that contains the same meta-data as the response itself, and such notifications may then be periodically and asynchronously sent back along the request path.

The meta-data in such notifications, as well as that in the reply message itself; may be used by request routers **112** to update local models of remote zones **70**-**74** and the respective nodes **60**-**64**. The meta-data may be used to provide client hosts **135** and intermediate proxies with relatively up-to-date information for each host regarding its capacity, average service latency, expected load, and so on, thereby promoting efficient routing of requests. The information received by the client host **135** in this manner may be more current than information obtained through aggregation using the service communicator **116**. Accordingly, in an exemplary embodiment, request routers **112** may be configured to give the information higher confidence and to prefer it. Moreover, the meta-data may contain information regarding hosts **137** which the request router **112** did not know through the service communicator **116** (e.g., host S3 for client host **135**). In that case, the request router **112** may add these hosts **137** in its routing table to use later for direct dispatch, as described below in connection with FIG. **16**.

With regard to the network latency, the network latency to a service host **137** from the client host **135** may be measured (e.g., using the round trip time (RTT) value obtained from TCP SOCKINFO system calls). Although this may not reflect the bandwidth of the network; other network monitoring tools may be used to enhance this model, if desired.

At step **204**, the information obtained during step **202** is used to calculate the end-to-end latency for each of the candidate hosts, e.g., using Eq. (2) as described above. At step **206**, the candidate hosts **137** are weighted in accordance with the end-to-end latencies for each of the hosts. At step **208**, the best host is selected based on the weightings for each host **137** in the set of candidate hosts **137**. The request is then routed to the selected host **137**.

2. Direct Dispatch

In an exemplary embodiment, the client host **135** may be permitted in some circumstances to dispatch service requests directly to a leaf node **60** based on information contained in a direct dispatch list. By dispatching to hosts **15** within the direct dispatch list, rather than to intermediate proxies, the system avoids any redirection latency (RL) thereby reducing overall end-to-end latency. The client host **135** may also be permitted to dispatch to intermediate proxies in the same manner, thereby achieving some of the benefits of dispatching directly at a leaf node **60** and some of the benefits of dispatching at the root node **64**.

At step **222**, the client host **135** maintains and updates its local model of the tree structure (including latency information) based on the meta-data received in responses to service requests. In an exemplary embodiment, when the latency data is provided by the service hosts **137**, the clients hosts **135** include a time-to-live (TTL) value for the meta-data. For example, the TTL value may be attached to the meta-data values updated by the hosts **137** that served and routed the request. Upon the receipt of the response, the request router **112** of the client host **135** adds the end-host in a direct-dispatch list, but only for TTL seconds. (If the request router **112** of the client host **135** already knows a particular host **137**, the TTL value may merely be updated.)

The TTL value is a time period during which the reported load of a service host **137** (learned through meta-data, as described above) is expected to be valid. The TTL value may be set by the host **137** based on its current utilization (e.g., which may be measured as the fraction of processes which are busy, and which may be smoothed over time). In an exemplary embodiment, the utilization of a host **15** is divided into three zones: underloaded, nearloaded and overloaded. A host **15** may be designated as underloaded if its utilization is less than 0.5, nearloaded if its between 0.5 and 0.8, and overloaded otherwise. The use of such threshold values avoids overloading of hosts through direct dispatch. If a host **15** is underloaded, its TTL value may be high (e.g., 3 minutes) and may decrease with increasing load. Effectively, the TTL value may be thought of a measure of how long the host wants to be remembered by a client host **135**.

At step **224**, the next time the request router **112** of the client host **135** needs to dispatch a request, the request router **112** first checks the direct-dispatch list and, at step **226**, determines whether any service hosts **137** are available for direct dispatch. At step **228**, if there are hosts **137** available for direct dispatch, then the client host **135** performs latency-based weighted dispatch between these hosts **137**. On the other hand, at step **230**, if the list is empty, then the client host **135** switches to regular routing through the list of hosts **137** it knows through the service communicator **116**, The list may become empty if hosts **137** become overloaded. For example, if a host **137** gets overloaded (e.g., due to background administration tasks such as disk backup, or due to a long-executing service request), then the host **137** may set its TTL value to zero, thereby avoiding direct dispatch and allowing dispatch only through proxies learned using the service communicator **116**.

Once a host **137** is added to the direct-host list, and if the request router **112** always dispatches its requests to this host, the list will always contain only a single element thereby potentially causing a herd-effect. To avoid such a herd effect and to facilitate the population of more hosts **137** into the direct-host list, the direct-host list may be used only with a certain probability (e.g., a configurable default value of 0.95). In an exemplary embodiment, the default probability value may take into account a tradeoff between redirection latency (RL) reduction and learning about new hosts to avoid the herd-effect.

In an exemplary embodiment, the client host **135** may be permitted to dispatch service requests at any level in the tree structure. For example, during a near-loaded scenario, it may be desirable to send a request to proxies in the higher levels (level 1 or higher in the service communicator **116** tree structure) as they may represent more capacity than a single end-host, and they may perform better load balancing through the aggregation of multiple client workloads in a more centralized queue.

To permit dispatching at intermediate levels of the tree structure during request routing, each service host **137** in the request path adds its status information along with a TTL value to the meta-data. Upon the receipt of this meta-data, the client request router **112** adds these hosts **137** in the direct-dispatch list. The TTL value of the service proxies may increase with increasing hierarchy depth (i.e., proxies at level 3 may have a higher TTL than proxies at level 2). The TTL values may also be determined based on an aggregation of the utilization of all hosts **137** within the subtree represented by the proxy, where the aggregation function is the weighted average of utilizations of all hosts within that subtree. By remembering proxies higher in the hierarchy for a longer time, the request routers **120** may smoothly transition between dispatching directly to end-hosts **137** (in order to avoid Redirection Latency) and a more centralized scheduler (which would reduce queuing latency at the end-host and hence Service Latency). Centralized queuing may be beneficial in high load situations as it uses a common entry point for queuing all client requests and allows the system to do effective dispatch of requests and/or load shedding. As loading increases, service requests tend to be dispatched at higher levels, because the TTL values are smaller. Lower level hosts **137** are forgotten more quickly than higher level hosts **137**, which are assigned higher TTL values. As loading decreases, the TTL values increase, causing service requests to be directly dispatched to lower levels in the tree structure. Because the service requests are dispatched at a lower level, the routing latency decreases. Thus, routing algorithm **120** adaptively dispatches loads at an appropriate level in the tree structure based on current loading conditions to attain the fastest response time. The request routers **120** may therefore make an appropriate tradeoff between network locality, redirection overhead, and end-host queuing, with the ultimate goal of reducing end-to-end latency.

3. Load Prediction

As described above, each request router **112** may append its load information (e.g., predicted SL and RL) in the meta-data of the response sent back to client hosts **135** and the request routers **112** upstream in the routing path (which are informed through completion notifications). Since client hosts **135** and intermediate proxies use this information to route requests, it is desirable for this information to avoid being skewed by temporary load fluctuations, such as flash crowds. Flash crowds are events when an application experiences an orders of magnitude increase in request rate from legitimate clients.

The expected service latency, and the redirection latency, for incoming requests may be calculated using exponential smoothing predictors. Even though exponential smoothing predictors operate satisfactorily for predicting latencies at a steady state, they often do not operate satisfactorily for predicting events such as hotspots or flash crowds. Linear-fit predictors may be used to detect flash crowds. The linear-fit predictors predict the expected latency for the near future (e.g., two minutes in the future). If predicted latency exceeds a certain threshold, then TTL values are set to zero. This enables the system to perform a more centralized queuing, and possibly load shedding, at higher levels and hence handle flash crowds effectively.

In another exemplary embodiment, if an application on a service host **137** is generating erroneous responses (which are often generated faster than legitimate responses), the routing system **55** is able to detect them as invalid responses. For example, the client hosts **135** may provide messaging to the global communicator **114** indicating that a particular service **118** is providing invalid responses, and the global communicator **114** may relay the information to other client hosts **135** to warn of the potentially failing service host **137**.

It should be noted that although flowcharts may be provided herein to show a specific order of method steps, it is understood that the order of these steps may differ from what is depicted. Also, two or more steps may be performed concurrently or with partial concurrence. Such variation will depend on the software and hardware systems chosen and on designer choice. It is understood that all such variations are within the scope of the invention. Likewise, software and web implementations of the present invention could be accomplished with standard programming techniques with rule based logic and other logic to accomplish the various database searching steps, correlation steps, comparison steps, and decision steps. It should also be noted that the word "component" as used herein and in the claims is intended to encompass implementations using one or more lines of software code, and/or hardware implementations, and/or equipment for receiving manual inputs. It is to be understood that any method steps as recited herein (e.g., in the claims) may be performed by a configuration utility (e.g., Java™-based) executed by a computing device based on input by a user. Of course, according to various alternative embodiments, any suitable configuration utility, application, system, computing device, etc. may be used to execute, implement and/or perform method steps as recited in this disclosure (including the claims).

The invention is described above with reference to drawings. These drawings illustrate certain details of specific embodiments that implement the systems and methods and programs of the present invention. However, describing the invention with drawings should not be construed as imposing on the invention any limitations associated with features shown in the drawings. The present invention contemplates methods, systems, and program products on any machine-readable media for accomplishing its operations. The embodiments of the present invention may be implemented using an existing computer processor, or by a special purpose computer processor incorporated for this or another purpose or by a hardwired system.

As noted above, embodiments within the scope of the present invention include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media which can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, PROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a machine, the machine properly views the connection as a machine-readable medium. Thus, any such connection is properly termed a machine-readable medium. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions comprise, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machine to perform a certain function or group of functions.

Embodiments of the invention have been described in the general context of method steps which may be implemented in one embodiment by a program product including machine-executable instructions, such as program code, for example, in the form of program modules executed by machines in networked environments. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Machine-executable instructions, associated data structures, and program modules represent examples of program code for executing steps of the methods disclosed herein. The particular sequence of such executable instructions or associated data structures represent examples of corresponding acts for implementing the functions described in such steps.

Embodiments of the present invention may be practiced in a networked environment using logical connections to one or more remote computers having processors. Logical connections may include a local area network (LAN) and a wide area network (WAN) that are presented here by way of example and not limitation. Such networking environments are commonplace in office-wide or enterprise-wide computer networks, intranets and the Internet and may use a wide variety of different communication protocols. Those skilled in the art will appreciate that such network computing environments will typically encompass many types of computer system configurations, including personal computers, hand-held devices, multi-processor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, and the like. Embodiments of the invention may also be practiced in distributed computing environments where tasks are performed by local and remote processing devices that are linked (either by hardwired links, wireless links, or by a combination of hardwired or wireless links) through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

An exemplary system for implementing the overall system or portions of the invention might include a general purpose computing device in the form of a computer, including a processing unit, a system memory, and a system bus that couples various system components, including the system memory to the processing unit. The system memory may include read only memory (ROM) and random access memory (RAM). The computer may also include a magnetic hard disk drive for reading from and writing to a magnetic hard disk, a magnetic disk drive for reading from or writing to a removable magnetic disk, and an optical disk drive for reading from or writing to a removable optical disk such as a CD-ROM or other optical media. The drives and their associated machine-readable media provide nonvolatile storage of machine-executable instructions, data structures, program modules, and other data for the computer.

The foregoing description of embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention. The embodiments were chosen and described in order to explain the principals of the invention and its practical application to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. A computer-implemented method comprising:

receiving a service request;

determining which of a plurality of candidate host computing devices to use for servicing the service request by at least:

for particular candidate host computing devices of the plurality of candidate host computing devices, assigning a weighting to the particular candidate host computing device based in part on latency information representing a service latency reflecting a queuing latency and a time required to process the service request by the particular candidate host computing device; and

selecting a candidate host computing device from the particular candidate host computing devices for servicing the service request based, at least in part, on the respective weighting assigned to each of the particular candidate host computing devices; and

routing the service request to the selected candidate host computing device.

2. The method of claim **1**, wherein determining which of the plurality of candidate host computing devices to use for servicing the service request comprises accessing information about a hierarchy, the plurality of candidate host computing devices being logically defined as having locations within the hierarchy.

3. The method of claim **2**, wherein the hierarchy further comprises a first level including a plurality of leaf nodes, wherein individual leaf nodes correspond to particular ones of the plurality of candidate host computing devices; and a second level defining a first plurality of zones, wherein individual zones comprise a subset of the plurality of leaf nodes.

4. The method of claim **3**, wherein the hierarchy further comprises a third level including a second plurality of zones which each comprise a subset of the first plurality of zones, and a fourth level including a root node associated with the plurality of leaf nodes, the first plurality of zones, and the second plurality of zones.

5. The method of claim **1**, wherein the assigned weighting for each of the particular candidate host computing devices is based in part on a network latency for each of the particular candidate host computing devices, and wherein the network latency is reflected in the latency information for each of the particular candidate host computing devices.

6. The method of claim **1**, wherein selecting a candidate host computing device for servicing the service request further comprises pseudo-randomly selecting a candidate host computing device from the particular candidate host computing devices based in part on measured latencies for the particular candidate host computing devices in accordance with the weighting assigned to the particular candidate host computing devices.

7. A system comprising:

a plurality of candidate host computing devices;

wherein the system is configured to:

receive a service request;

determine which of a plurality of candidate host computing devices to use for servicing the service request by at least:

for particular candidate host computing devices of the plurality of candidate host computing devices, assigning a weighting to the particular candidate host computing device based in part on latency information representing a service latency reflecting a queuing latency and a time required to process the service request by the particular candidate host computing device; and

selecting a candidate host computing device from the particular candidate host computing devices for servicing the service request based, at least in part, on the respective weighting assigned to each of the particular candidate host computing devices; and

route the service request to the selected candidate host computing device.

8. The system of claim 7, wherein the plurality of host computing devices are heterogeneous and have different processing capacities, and wherein the system is further configured to select the candidate host computing device based at least in part on the processing capacities of the candidate host computing devices when making routing decisions.

9. The system of claim 7, wherein the assigned weighting for each of the particular candidate host computing devices is based in part on a network latency for each of the particular candidate host computing devices, and wherein the network latency is reflected in the latency information for each of the particular candidate host computing devices.

10. The system of claim 7, wherein the plurality of host computing devices are logically defined as having locations within a hierarchy of a service framework, wherein the hierarchy further comprises:

a first level including a plurality of leaf nodes, wherein individual leaf nodes correspond to individual host computing devices of the plurality of host computing devices;

a second level defining a first plurality of zones, wherein individual zones comprise a subset of the plurality of leaf nodes;

a third level including a second plurality of zones, each of the second plurality of zones comprises a subset of the first plurality of zones; and

a fourth level including a root node associated with the leaf nodes, the first plurality of zones, and the second plurality of zones.

11. The system of claim 7, wherein the system is further configured to route the service request to the selected candidate host via at least one proxy host.

12. A non-transitory computer-readable medium bearing computer-executable instructions which, when executed on a computing device, direct the computing device to:

receive a service request;

determine which of a plurality of candidate host computing devices to use for servicing the service request by at least:

for particular candidate host computing devices of the plurality of candidate host computing devices, assigning a weighting to the particular candidate host computing device based in part on latency information representing a service latency reflecting a queuing latency and a time required to process the service request by the particular candidate host computing device; and

selecting a candidate host computing device from the particular candidate host computing devices for servicing the service request based, at least in part, on the respective weighting assigned to each of the particular candidate host computing devices; and

route the service request to the selected candidate host computing device.

13. The non-transitory computer-readable medium of claim 12, wherein the plurality of candidate host computing devices are heterogeneous and have different processing capacities, and wherein the computer-executable instructions further configure the computing device to account for the processing capacities of the plurality of candidate host computing devices when selecting a candidate host computing device.

14. The non-transitory computer-readable medium of claim 12, wherein the computer-executable instructions further configure the computing device to pseudo-randomly select a candidate host computing device from the plurality of candidate computing devices based on measured latencies for the particular candidate host computing devices in accordance with the assigned to the particular candidate host computing devices.

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